TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

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CHARACTERIZATION OF A DOWNDRAFT GASIFIER FUELED BY BAMBOO – A PILOT PROJECT IN MEXICO

Master of Science Thesis

Examiners: Professors Risto Raiko & Antti Oksanen
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ABSTRACT

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The world is at turning point regarding energy issues. Especially in developing countries the demand for electricity is rising steeply, nobody really knows how long the fossil fuels are going to last, their price fluctuations are hard to foresee and the climate change is a concerning fact. Hence, there is an increasing need to look for alternative, clean and sustainable energy sources and to control the greenhouse emissions.

Biomass gasification is a promising technology for using local feedstock to produce synthesis gas that can be applied for electricity production. It might also be a potential technology for some rural areas where no power grid exists. Different biomasses can be applied for producing electricity and this study concentrates on gasification of bamboo in Mexico. Bamboo has not been investigated for energy production purposes in Mexico before and also gasification is a newer and less researched technology in the country. Another objective of this thesis is to find the optimal process variables to guarantee the production of a good quality synthesis gas in a fixed bed downdraft gasifier that is being built for the project FSE-152364 SENER-CONACYT.

The first part of the study offers an overview of the gasification technology based on several literature sources. The energetic valuation of bamboo is examined through the laboratory analyses carried out at the Electrical Research Institute in Cuernavaca, Mexico. The gasification process is simulated using a software program called Thermoflex. In order to find the best possible process variables, a series of sensitivity analyses is carried out. After that one optimal simulation is discussed in more detail. In the end, the experiments done with an experimental gasifier built in Huatusco, Veracruz Mexico are presented. The preliminary results of the synthesis gas composition are listed and analyzed. Also, the results obtained by Thermoflex are compared with the calculations elaborated for this study and with the results found in the literature.

The results show that bamboo is a satisfactory fuel for a downdraft gasifier. Its incredible rate of accumulating biomass makes it an interesting option for energy production. The heating value of the synthesis gas, cold gas efficiency and the system efficiency are in the normal range according to literature references. The experimentally obtained results show however that the process is not well controlled yet. Thus, improvements and more test runs based on the results found in this thesis must be carried out in order to obtain a stable gas production and good quality synthesis gas.

TIIVISTELMÄ

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Energiamaailma elää tällä hetkellä valtavassa muutostilassa. Etenkin kehitysmaissa sähköenergian tarve on jyrkässä kasvussa, fossiilisten polttoaineiden riittävyyttä sekä niiden hintaheilahteluja on vaikea arvioida ja ilmastonmuutos on huolestuttava tosiasia. Tämä kaikki lisää painetta etsiä vaihtoehtoisia ratkaisuja puhtaan ja kestävän energian tuottamiseksi sekä kasvihuonepäästöjen hillitsemiseksi.

Biomassan kaasutus on lupaava teknologia paikallisen, uusiutuvan polttoaineen hyödyntämiseksi sähköntuotannossa. Se saattaa myös tarjota ratkaisun energiantuotantoon alueille, jotka ovat sähköverkon ulottumattomissa. Monet erilaiset biomassat soveltuvat energiantuotantoon ja tämä työ keskittyy bambun kaasuttamiseen Meksikossa. Bambua ei ole aiemmin tutkittu energiantuotantomielessä Meksikossa ja myös kaasutus on hyvin uusi teknologia maassa. Toinen tämän työn tavoitteista on löytää optimaaliset prosessiarvot hyvälaatuisen synteesikaasun tuottamiseksi kiinteäpeti-myötävirtakaasuttimella. Kaasutinta rakennetaan parhaillaan tätä projektia (FSE-152364 SENER-CONACYT) varten.

Työn ensimmäinen osa tarjoaa kattavan kirjallisuuskatsauksen kaasutusteknologiaan. Bambun ominaisuuksia ja soveltuvuutta kaasutettavaksi tarkastellaan Electrical Research Instituten (Cuernavaca, Meksiko) laboratorioanalyysien perusteella. Kaasutusprosessin simulointiin käytetään Thermoflex-nimistä ohjelmistoa. Aluksi suoritetaan sarja herkkyysanalyysejä, joiden avulla pyritään löytämään parhaat mahdolliset toimintaolosuhteet kaasuttimelle. Tämän jälkeen yhtä optimaalista simulointia tarkastellaan yksityiskohtaisemmin. Lopuksi käsitellään kaasun koostumusmittauksia, jotka suoritettiin kokeellisella kaasuttimella Huatuscossa, Veracruzissa Meksikossa, ja esitellään niiden tulokset. Myös Thermoflexillä saatuja tuloksia verrataan tätä työtä varten tehtyjen tasapainolaskujen tuloksiin sekä kirjallisuudesta löydettyihin arvoihin.

Työn tulokset osoittavat, että bambu on tyydyttävä polttoaine myötävirtakaasuttimelle. Sen valtava kasvunopeus tekee siitä kiinnostavan vaihtoehdon energiantuotantoprosesseihin. Tuotekaasun lämpöarvo, kaasuttimen ja koko systeemin hyötysuhde ovat normaaleissa, kirjallisuudesta löydetyissä vaihteluväleissä. Kuitenkin kokeellisesti mitatut tulokset osoittavat, että prosessia ei vielä hallita niin hyvin kuin pitäisi. Siksi parannuksia sekä useita testiajoja tullaan vielä tekemään tämän työn tulosten pohjalta, jotta pystytään tuottamaan hyvälaatuista synteesikaasua tasaisella tahdilla.

PREFACE

The academic year of 2011-2012 I spent living the time of my life in Mexico. When it was time to go home I promised myself that it wouldn't be the last time my feet touch the ground of this beautiful country. I kept my promise and by a few lucky coincidences ended up travelling here again 1.5 years later.

This thesis would never have happened without a contribution of various institutions and people. It was conducted with a scholarship from the Mexican Government, through the Ministry of Foreign Affairs (Secretaría de Relaciones Exteriores). I also received financial support from the International Centre for Mobility (CIMO) and Tampere University of Technology. My sincerest thanks for all the financing parties who made my stay in Mexico possible.

Professors Risto Raiko and Antti Oksanen, I appreciate your guidance and advice, especially in the beginning of the whole process. Thank you for giving a gentle push into the right direction.

I also want to thank various people from the Electrical Research Institute where I spent 9 months writing the thesis. Nora Pérez Flores, thank you for organizing everything so well and taking good care of me upon my arrival; Hipólito Romero Tehuitzil, thank you for guiding me along the process, teaching me pieces of Mexican culture and sharing your expertise; Jorge Huacuz Villamar, thank you for your wise words and constructive feedback; the whole office of Alternative Energy, thank you for the inspirational spirit and the exercise pause everyday at 11:45 am.

Bambuver A.C. and all its employees in Huatusco Veracruz, I have to give credit for your cooperation and helping us to carry out various test runs. Without you this project would not exist.

Most importantly I want to express my gratitude for my friends and family in Finland who gave me the extra kick in the butt to pack my bags and leave for Mexico - again. Sini Tontti, I know you'll always be there for me – no matter where I am. I also feel grateful for knowing such amazing people from Mexico. You made my stay unforgettable.

"La vida es como montar en bicicleta. Para mantener el equilibrio, hay que seguir avanzando".

In Cuernavaca, Mexico, December 19th, 2014

Julia Salovaara

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ABBREVIATIONS AND NOTATION

$\eta_{cold\ gas}$	Cold gas efficiency [%]
$\eta_{overall}$	Overall system efficiency [%]
η_{engine}	Engine efficiency [%]
$\eta_{generator}$	Generator efficiency [%]
ρ_{bulk}	Bulk density [kg/m^3]
ρ_i	Density of a substance i [kg/m^3]
Ψ	Relative humidity [%]
A	Mass flow of air [kg/h]
A_0	Pre-exponential constant in Arrhenius form [1/s]
A_{throat}	Throat area of the downdraft gasifier [m^2]
A/F-ratio	Air-Fuel-ratio [kg air/kg fuel]
Ar	Argon
B_g	Hearth load [m^3/cm^2*h]
C	Carbon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
COS	Carbonyl sulfide
d_{throat}	Throat diameter of the gasifier [m]
E	Activation energy [kJ/mol]
ER	The equivalence ratio
f	Frequency [1/s or Hz]
F	Mass flow of fuel (bamboo) [kg/h]
G	Volumetric flow of the synthesis gas [m^3]
G/F-ratio	Gas to fuel ratio [m^3 of gas/1 kg of bamboo]
H, H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulfide
HCV	Higher calorific value = HHV [J/kg or J/m^3]
HHV	Higher heating value = HCV [J/kg or J/m^3]
ICE	Internal Combustion Engine
k_i	The reaction rate constant of i
LCV	Lower calorific value = LHV [J/kg or J/m^3]
LHV	Lower heating value = LCV [J/kg or J/m^3]
m	Reaction order with respect to the gas partial pressure
M_i	Molecular weight of a substance i [g/mol]
MC	Moisture content [w-%]
n	Number of cylinders in an engine
n_i	The amount of a substance i

N, N_2	Nitrogen
NaOH	Sodium hydroxide
Nm^3	Normal cubic meters i.e. reported in STP
O, O_2	Oxygen
p	Pressure [bar or pascal]
p_i	Partial pressure of a substance i on the char surface [bar]
PAH	Polycyclic aromatic hydrocarbons
ph	Partial pressure of vapor in the air [mbar]
ph'	Pressure of saturated vapor [mbar]
r_b	Rate of Boudouard reaction [1/s]
R	The universal gas constant, 8.314 kJ/molK
RPM	Rounds per minute
S	Sulphur
SO_2	Sulphur dioxide
STP	Standard conditions for temperature and pressure
T	Temperature [°C or K]
v_i	Volumetric fraction of i in the synthesis gas
V_g	Flue gas intake rate of an engine [m^3/h]
V_m	Molar volume of gas [dm^3/mol]
V_s	Swept volume of an engine [m^3/h]
$Weight_{dry}$	Weight when a sample has been oven dried [kg]
$Weight_{green}$	Weight when a sample has not yet been oven-dried [kg]
W-%	Weight- or mass-percent
y_i	Mole fraction or volume fraction of a substance i

1. INTRODUCTION

Mexico has traditionally been a country where industries and economy are based on oil and gas. The energy sector still relies heavily on fossil fuels as seen in figure 1.1. The utilization of renewable energies (other than hydro) is a fairly new phenomenon in the country. Non-hydro renewables represented only 3 % of the total electricity generation in 2013. (EIA 2014). However, changes in the attitudes and politics are slowly starting to appear: the target for 2024 is that 35 % of the electricity in Mexico would be produced by renewable sources. (IEA 2014) Mexico has also declared a plan to reduce carbon dioxide emissions by 50 % by 2050 based on the levels in 2002. (Romero-Hernández et al. 2013, p. 24) Solar and wind energy have already started to grow fast and according to the EIA, Mexico is ready to become one of the world's fastest growing wind energy producers. (EIA 2014)

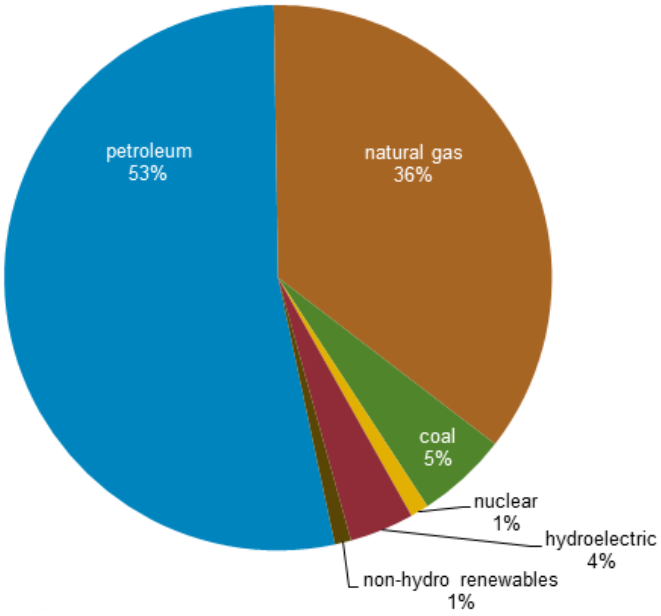

Figure 1.1 *Total Energy Consumption in Mexico in 2012 (EIA 2014, p.2)*

However, not all the places are suitable for wind or solar energy. Another renewable option, that could guarantee more stable production which is not dependent on weather conditions, is the gasification of biomass. Gasification is a thermochemical process where a limited amount of oxygen or air reacts with feedstock in a high temperature producing synthesis gas. Nevertheless, if renewable energy is something new for Mexico, biomass gasification is even newer. Until the year 2011 there was only one documented investigation project of wood gasification in Mexico (Cerutti et al. 2011; Nava et al. 2009). As seen in figure 1.2 on the right, Central and South America have the

smallest share of using gasification technology in the world. The graph on the left shows that gasification of different fossil fuels exists to great extent but the share of biomass and waste gasification is still very modest. The worldwide installed capacity of biomass gasification systems was only 1.4 GW_{th} in 2011. (Cerutti et al. 2011, p.23)

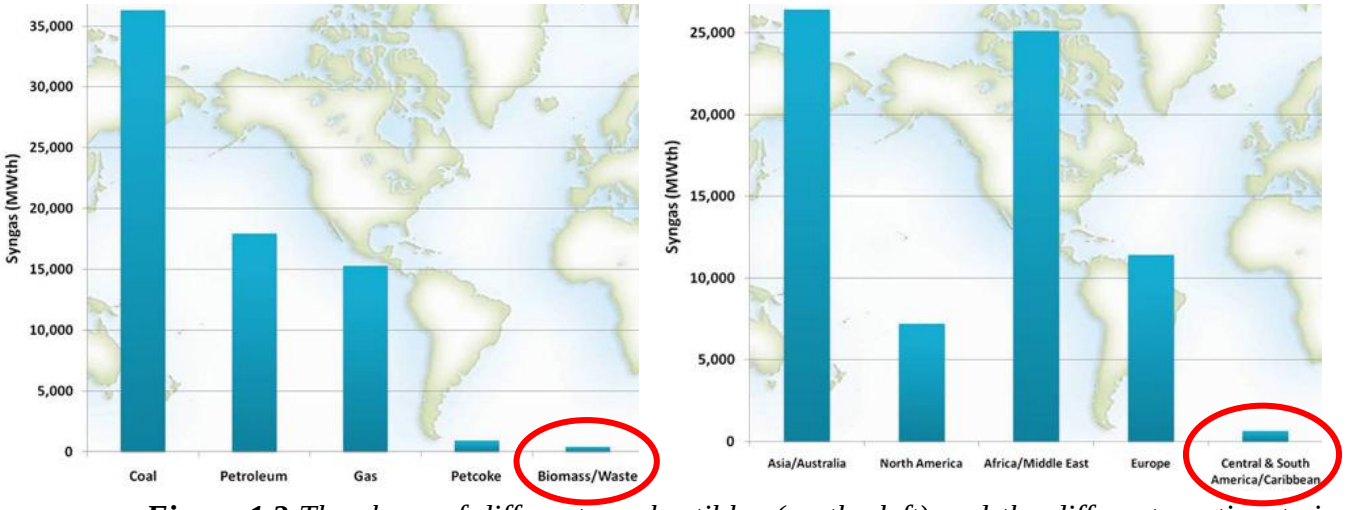

Figure 1.2 *The share of different combustibles (on the left) and the different continents in gasification in 2010. (NETL 2010)*

A big challenge at the moment and in the future is getting all human beings an access to electricity and at the same time stop the climate change. According to IEA (2014) there are 1.3 billion people worldwide who still live without electricity. Most of these people live in developing countries and rural areas where also population growth has the biggest rate. When these areas start to become wealthier they are going to need increasing amounts of energy. In Mexico 2.2 % of the population does not have access to the power grid. (INEGI 2014) This equals approximately to 2.5 million people. The importance of generating electricity by renewable sources is extremely high in these areas because they can contribute to climate change – either positively or negatively. Gasification could offer one option for electricity generation in rural areas because it is a proven technology for producing power at small scales using locally available biomasses. It also creates other economical and social benefits for the area.

The applicability of various, different biomasses for gasification has been investigated around the world. Especially woody biomasses have turned out to be appropriate for the technology in question. However, every biomass is different and the gasifier needs to be designed according to the specific qualities of each biomass. The aim of this study is to investigate bamboo as a fuel for a small scale downdraft gasifier and find the optimal process parameters for producing good quality synthesis gas.

Bamboo as a gasification combustible has not been investigated in Mexico before. Also in general, studies on bamboo gasification in the open literature are rather limited. Some investigations carried out in Asia and Africa exist (for example Kerlero de Rosbo & de Bussy 2012; Ganesh 2003) but most of the other studies of thermal conversion of bamboo discuss rather the production of activated carbon (Choy et al. 2005; Ip et al.

2008; Lo et al. 2011) or bio-oil (Krzesińska & Zachariasz 2007; Lou et al. 2010; Jiang et al. 2012) - not the gasification.

1.1 Structure of the Investigation

This thesis is part of the Electrical Research Institute's project FSE-152364 called "Diseño del prototipo para la generación eléctrica mediante gasificación de bambú" which in English means "Design of a Prototype for Generating Electricity through Gasification of Bamboo". The project is carried out in cooperation with several parties. The Institute of Electrical Research and Bambuver A.C. are responsible for planning and executing the project and it is funded by the Sustainable Energy Fund of SENER-CONACYT. Bambuver A.C. is a family-owned, nonprofit organization that cultivates bamboo in Huatusco, Veracruz. An experimental gasifier is located in their workshop and the pilot plant will be installed in a hotel, owned by the same family.

The objective of this study is to find the optimal operation variables for a fixed bed downdraft gasifier that uses bamboo as a fuel. The other target is to examine the applicability of bamboo for energy production purposes. A comprehensive literature review, that covers the history of gasification, the most important thermochemical processes, tar production, process stability, different gasifier technologies and possible hazards, is done in chapter 2. Chapter 3 concentrates on the qualities of bamboo in the energy production's point of view. Chapter 4 presents the Huatusco project and the gasification plant. After that, in chapter 5, all the calculations done for this study are represented. First a series of Thermoflex simulations are carried out in order to find the optimal range for different parameters. Then an ideal, more detailed simulation is done. After that calculations elaborated for this study are presented in order to be able to understand and compare the results obtained in Thermoflex.

An experimental part is discussed in chapter 6. Unfortunately the time range of this thesis was not enough to carry out experiments on the pilot plant (it was still under construction). The experimental gas testing discussed in chapter 6 is done with the experimental, small scale gasifier (~40 % of the real size). More test runs, investigation and development in the project FSE-152364 will be carried out in the future utilizing the results obtained in this thesis. At the end of the work all the results are summarized and analyzed and the conclusions discussed.

2. LITERATURE REVIEW OF GASIFICATION

Gasification has already been a known technology since the 19th century and it has been developed actively mainly during different energy crisis. Now the growing threat of climate change has aroused interest towards this technology and the investigation has been active for a longer period of time. The section 2.1 discusses the history of gasification in more detail and section 2.2 offers an overview of the topic.

Gasification is a thermochemical conversion process and the different reactions that occur inside the gasifier are explained in section 2.3. The reaction kinetics greatly affects the behavior of a gasifier especially when the biomass is being gasified. This topic is briefly discussed in section 2.4. One of the biggest obstacles, that prevents gasification from becoming a widely used technology, is the tars that cause a lot of troubles in gasifier equipment. They are discussed in section 2.5. Other factors affecting the gasifier stability are listed in section 2.6. During the many years of investigation a great variety of different kinds of gasifier technologies has been developed but only the most common ones are presented in this study, in section 2.7. Although gasification represents a cleaner technology, it has an effect on the environment. It also might cause different kinds of hazards for the users. These are discussed at the end of chapter 2.

2.1 History

The basic idea of a gasifier is rather simple: a feedstock enters the gasifier and through different oxidizing and reduction processes synthesis gas is produced. Gasifying of solid fuels is not a new invention. Gasification became a commercial process in London as early as in 1812 and the gas was first used as town gas for lighting and cooking purposes. (Higman, C. & Van Der Burgt, M. 2008, p. 2; Quaak et al. 1999, p.43) Using coal and wood as gaseous fuels in an internal combustion engine first started in England in 1881. (Hyytiäinen et al. 1944, p. 15) The devices were primitive and the development was slow in whole Europe until the First World War. After the war years, France, Germany and Sweden were especially concentrated on building gasifiers and vehicles that used wood gas as a fuel. The states of these countries supported the development work significantly because they understood the high financial and military value of having domestic fuel. (Hyytiäinen et al. 1944, p.17.)

In Finland, the common interest towards gas as a fuel arouse during the II World War because of the shortage of gasoline. A strong development phase began in 1940, after the Finnish Winter War, when the delivery of gasoline stopped completely. Without wood gas generators the whole country would practically have been paralyzed.

Hyytiäinen et al. (1944, p.19) state that all trucks, buses and those private cars, that were allowed to operate, ran satisfactorily by using wood gas.

Although wood gas saved the Finnish society, it was hard, dirty and dangerous to use. It also reduced the engine power compared with gasoline. When the world had recovered from the war years and there was no longer need to control the consumption of gasoline, the wood gas cars quickly became a rarity.

The first oil crisis in the 1970s re-started the development of gasification processes and different gasifiers. A lot of new investments were done and some technological advancement achieved. However, in the 1980s the oil production rose again and the price of oil declined which caused the interest towards gasification to fall again. (Higman, C. & Van Der Burgt, M. 2008, p.5-6; Quaak et al. 1999, p.43.)

During the last 10-15 years the gasification of biomasses has been studied with growing attention. That is because of rising and fluctuating costs of fossil fuels and increasing concern of climate change. Biomass offers a cleaner choice to produce energy by gasification or combustion because it is renewable and does not emit large amounts of harmful nitrogen oxides (NO_x) or sulfur dioxide (SO_2). (Quaak et al. 1999, p.12) Also local, oil independent, small scale production in the rural areas becomes possible with biomass gasification.

2.2 An Overview of Gasification

A course handout (Raiko 2012, p.124) briefly describes gasification as a process where oxygen or air reacts with a solid or liquid fuel in high temperature. The main product is synthesis gas and the secondary product ash. Higman & Van Der Burgt (2008) define gasification as conversion of any carbonaceous fuel to a gaseous product that has a usable heating value. Carbonaceous means any substance that is rich in carbon such as coal, oil, biomass and waste. (Higman & Van Der Burgt 2008, p.1) The synthesis gas can be used for instance in an internal combustion engine or in a gas turbine to produce electricity and heat. It is also suitable for cooking, refrigeration (gas refrigerators) and lighting, for process heat and for chemical synthesis (production of nitrogen fertilizers and other chemicals). (Reed & Gaur 2001, p.1-4)

It is important to make a difference between the conventional combustion technology and gasification although they both are close related thermochemical processes (Kristiansen 1996, p 17; Basu 2013, p.199). Kristiansen (1996) states, that in combustion, feedstock is burned using excess amount of air in order to ensure complete combustion. In the gasification process only 1/5 to 1/3 of stoichiometric oxygen is used. Basu (2013) declares that in gasification, energy is being packed into the chemical bonds of the product gas. This means that the syngas still has considerable heating value left. In combustion those bonds get broken, energy gets to release and the flue gas has no heating value left. That is because combustion oxidizes the hydrogen into water (H_2O) and carbon into carbon dioxide (CO_2). In gasification hydrogen is added to the

hydrocarbon feedstock and carbon is removed from it. This is how gases with higher hydrogen-carbon ratio are produced. (Basu 2013, p. 199.)

There are some advantages of gasifying and then burning over just burning the biomass. Wider range of different fuels (e.g. problematic waste) can be gasified cleanly and the produced synthesis gas has more applications than the solid fuel. The gas is easier and cheaper to distribute and control and it can be compressed so that its energy intensity increases. The gas burns purely because most of the impurities are removed already in the gasifier and its combustion is efficient and intense increasing the heat transfer an order of magnitude compared with solid biomass combustion. (Reed and Gaur 2001, p.1-4.) Gasification also produces lower SO_2 and NO_x emissions than a combustion system and can therefore lead to a reduction in acid rain. (Basu 2013, p.21)

The thermal conversion processes consist of a few different phases that are normally modeled consecutive (one after another). Nevertheless, no sharp boundaries between the phases exist and they happen partly simultaneously. These phases are preheating and drying of the matter, pyrolysis, gasification and combustion (Higman & Van Der Burgt 2008; Raiko 2012; Basu 2013.) They will be discussed next in section 2.3.

2.3 Thermal Conversion Processes in Biomass Gasification

According to Kristiansen (1999, p.17) the thermal conversion processes consist of the following phases:

$$\boldsymbol{Pyrolysis}: Biomass + Heat \rightarrow Charcoal + Liquids + Gases$$
$$\boldsymbol{Combustion}: Biomass + Stoichiometric\ oxygen \rightarrow Hot\ combustion\ products$$
$$\boldsymbol{Gasification}: Biomass + Gasifying\ agent\ (limited\ oxygen) \rightarrow Fuel\ gas + Ash$$

The phases without the heat fluxes are illustrated in figure 2.1. Also the drying phase is shown. The volatile matter forms a big part of biomasses (see subsection 3.3.1) and it is released in pyrolysis processes. Hence the principal task of biomass gasification is to convert these volatiles to permanent gases. A secondary task is to convert the charcoal to gas as seen in figure 2.1. (Reed & Das 1988, p. 27.) These processes will be analyzed in more detail in the next sections.

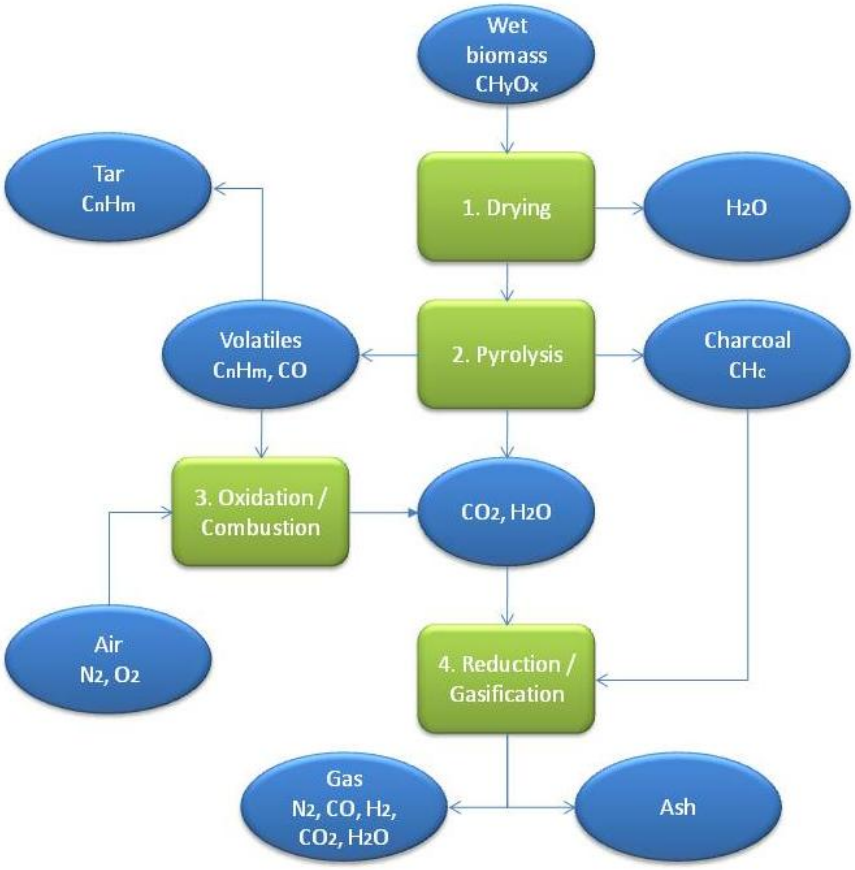

Figure 2.1 *The thermal conversion processes of biomass gasification (adapted from Jeanmart et al. 2007, p.4)*

2.3.1 Drying

Different biomasses usually include great amounts of moisture. Depending on the type of biomass the moisture content can rise up to 90 % on a dry basis (Basu 2013, p.76). If moist feedstock is gasified or combusted, a lot of energy is used: according to Basu (2013) every kilogram of moisture needs 2300 kJ of heat to vaporize and extra 1500 kJ is needed to heat up the feedstock to the temperature of 700 °C. This amount of energy comes from the exothermic reactions of the gasifier and is not recoverable which causes the decreasing of the heating value and a concern especially for energy applications. That is why the biomass should be pre-dried before feeding it into the gasifier. The moisture content of the feedstock in gasification should be between 10-20 %. (Basu 2013, p. 202.)

The proper preheating occurs inside the gasifier with the help of heat released from burning of the flue gases. When the temperature exceeds 100 °C, the loosely bound water in biomass evaporates. After that the extractive agents also start to volatilize. (Basu 2013, p.120.) As the temperature rises more, pyrolysis of the organic matter begins.

2.3.2 Pyrolysis

Pyrolysis is an essential and relatively fast reaction in a gasifier. It means thermal (=pyro) degradation (=lysis) of organic materials. They start to pyrolyze in elevated temperatures of 350-600 °C forming a hydrogen-rich fraction and a carbon-rich residue called char. (Kerlero de Rosbo & de Bussy 2012, p.25; Kristiansen 1999, p. 25.) The hydrogen-rich factor consists of condensable gases that can break down into non-condensable gases (a mixture of hydrogen, oxides of carbon, methane etc.) and light oils and tars. (Kristiansen, p.25; Basu 2013, p.68) Basu (2013) illustrates the pyrolysis process with the following general equation:

$$C_nH_mO_p(Biomass) + Heat \rightarrow \sum_{liquid} C_xH_yO_z + \sum_{gas} C_aH_bO_c + H_2O + C(char) \quad (2.1)$$

where the liquid, gaseous and solid yields can be seen. (Basu 2013, p.68)

Pyrolysis is an endothermic reaction which means that it requires an external source of energy in order to occur. In a pyrolyzer, the non-condensable gases can be burnt to heat it up while the condensable gases can be condensed into pyrolysis oils and further processed into bio fuels. (Kerlero de Rosbo & de Bussy 2012, p.25). However, the target in this study is not to produce bio-oils but maximize the production of char and non-condensable gases.

2.3.3 Combustion and Gasification

Gasification can be defined as thermal degradation when an oxidation agent is present whereas combustion (ideally described) could be defined as complete oxidation of the fuel. (Van Loo, S. & Koppejan, J. 2008, p.11) When the temperature exceeds 700 °C the gasification reactions begin. According to Kristiansen (1996, p.17) the principal equations of gasification of solid char can be summarized in five basic chemical reactions (the following equations 2.2-2.6). The char reacts with oxygen (O_2), carbon dioxide (CO_2), steam (H_2O) and hydrogen (H_2). Also the gases react within themselves producing the final syngas. (Kristiansen 1996, p.17; Higman & Van Der Burgt 2008, p.12) The reaction enthalpies ΔH of the following equations have been given for reference conditions of 25 °C and 1.013 bar. (Kristiansen 1996, p.19; Basu 2013 p. 121)

When carbon reacts with a low amount of oxygen, partial combustion (=gasification) occurs:

$$C + \frac{1}{2}O_2 = CO \qquad \Delta H = -111 \text{ kJ/mol} \quad (2.2)$$

The complete combustion of carbon occurs when an excess amount of oxygen is present:

$$C + O_2 = CO_2 \qquad \Delta H = -394 \text{ kJ/mol} \quad (2.3)$$

This reaction uses most of the oxygen fed into the gasifier and, as being highly exothermal, produces enough heat to dry the feedstock, break chemical bonds and thus rise the temperature inside the gasifier. Reaction (2.3) occurs in the oxidation/combustion zone of the gasifier. (Quaak et al 1999, p.85)

The gasification reaction with carbon dioxide is known as the Boudouard reaction:

$$C + CO_2 \leftrightarrow 2CO \qquad \Delta H = +172 \text{ kJ/mol} \qquad (2.4)$$

This reaction is driven by the heat produced by the equation (2.3) although it proceeds very slowly at temperatures below 1000 K (727 °C). Another endothermic reaction is gasification with steam, also known as the water-gas or water steam reaction:

$$C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H = +131 \text{ kJ/mol} \qquad (2.5)$$

This reaction between carbon and steam occurs in elevated temperature but is slow at temperatures below 1200 K (927 °C). The equations (2.4) and (2.5) are the main reactions of the reduction zone in the gasifier. (Quaak et al. 1999, p.86.)

The gasification with hydrogen (=hydro gasification reaction) also tends to be very slow - even a lot slower than the other reactions, except at high pressure. The chemical reaction is written as follows:

$$C + 2H_2 \leftrightarrow CH_4 \qquad \Delta H = -74.8 \text{ kJ/mol} \qquad (2.6)$$

When the moles and energy quantities of the equation (2.4) are reduced from the equation (2.5), the equation (2.7) is obtained. This is called the water-gas shift reaction (Kristiansen 1996, p. 19) or the CO shift reaction (Higman & Van Der Burgt 2008, p. 13; Basu 2013, p. 121):

$$CO + H_20 \leftrightarrow CO_2 + H_2 \qquad \Delta H = -41{,}2 \text{ kJ/mol} \qquad (2.7)$$

Accordingly, when (2.6) is subtracted from (2.5), the equation (2.8) is obtained. This is called the steam methane reforming reaction (Higman & Van Der Burgt 2008, p.13):

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \Delta H = -206 \text{ kJ/mol} \qquad (2.8)$$

The gas phase reactions (2.7) and (2.8) are important for the final gas quality. The equation (2.7) has an influence on the CO/H_2 ratio whereas the equation (2.8) increases the heating value of the syngas. (Kristiansen 1996, p.19). However, Higman & Van Der Burgt (2008, p.13) state that the reactions (2.2) and (2.5) are the most essential in most gasification processes.

To get a clearer picture of the char gasification reaction speeds, Basu (2013) summarizes them as follows: $R_{C+O_2} \gg R_{C+H_2O} > R_{C+CO_2} \gg R_{C+H_2}$. The char-oxygen reaction is the fastest and it quickly consumes all the oxygen of the gasifier. The char-steam reaction is three to five orders of magnitude slower than the char-oxygen reaction and the Bourdouard reaction six to seven orders of magnitude slower. Finally the char-hydrogen reaction is much slower than all the other reactions of the gasifier. (Basu 2013, p. 123.) The next section 2.4 discusses the reaction kinetics in more detail.

2.4 Reaction Kinetics of Biomass Gasification

Some of the reactions in a gasifier are neither instantaneous nor complete and thus all the reactants do not necessarily turn into products. (Basu 2013, p. 218) The chemical kinetics affects greatly the rate of heterogeneous gasification reactions (char+gas). Their rate depends mainly on the heat transfer inside a fuel particle which then again depends on its porosity. Biomasses tend to have a very porous structure which is dependent on the fuel type, the composition of the ash and the heat provided during the pyrolysis. (Raiko 2012, p.130.) The porosity of biomass char is in the range of 40-50 % whereas that of coal is only 2-18 %. Also the pores of biomass char are a lot larger, 20-30 μm, compared with coal char pores, ~$5*10^{-10}$ m. (Basu 2013, p. 203.)

Defining reaction rates is highly experimental work and very little data for bamboo was available. However, bamboo is very similar to other lignocellulosic biomasses (see chapter 3) and thus data found on them will be used in this study to get an idea of the behavior of reaction rates.

2.4.1 The Boudouard Reaction

According to Basu (2013) the char reactions play a major role in the design and performance of a gasifier. The most typical char reactions are the Boudouard reaction (2.4), the water-gas reaction (2.5) and the methanation reaction (2.6). When air or oxygen is used as a gasification medium, the Boudouard reaction is dominant, which is the case in this study. (Basu 2013, p 222.) Hence, it will be further investigated.

Basu (2013) gives some experimentally obtained values for lignocellulosic biomass chars such as birch (betula) and douglas fir (pseudotsuga menziesii). Since no information of bamboo was available, those values for wood presented by Basu were used in this study. To understand better the graphs on the next page, it is worth to revise the equations and calculations showed in Appendix 1 first.

The figure 2.2 below illustrates the Boudouard reaction rates of birch char. The rates below 800 °C are so small that the Boudouard reaction practically does not occur or it is very slow. After that the reaction rate quickly grows. Also the inhibiting effect of CO can be seen clearly.

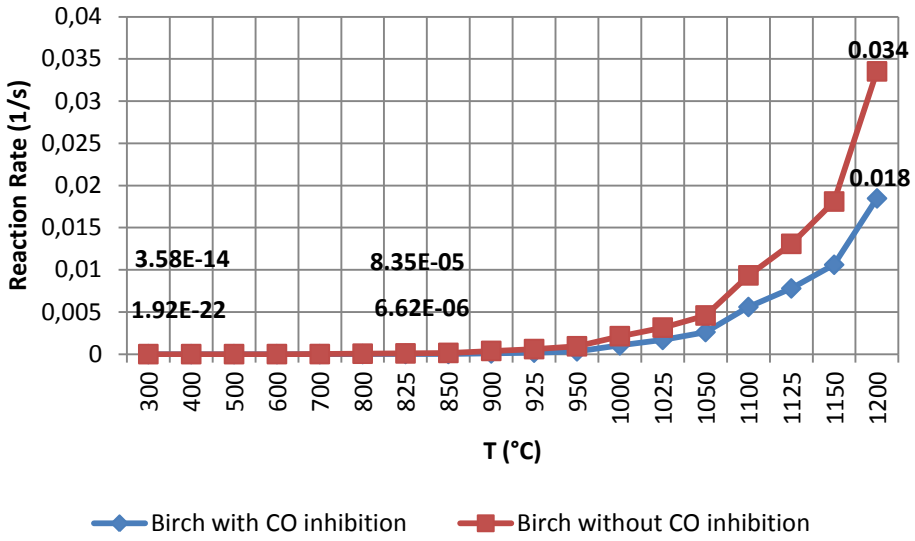

Figure 2.2 *Boudouard reaction rate on the function of temperature for birch char (own elaboration based on the calculations of Appendix 1).*

The figure 2.3 shows the results for douglas fir when CO inhibition is not considered. It can be seen that the rates are a lot higher than for birch (note the y-axis). This means that the Boudouard reaction is a lot faster when gasifying douglas fir instead of birch.

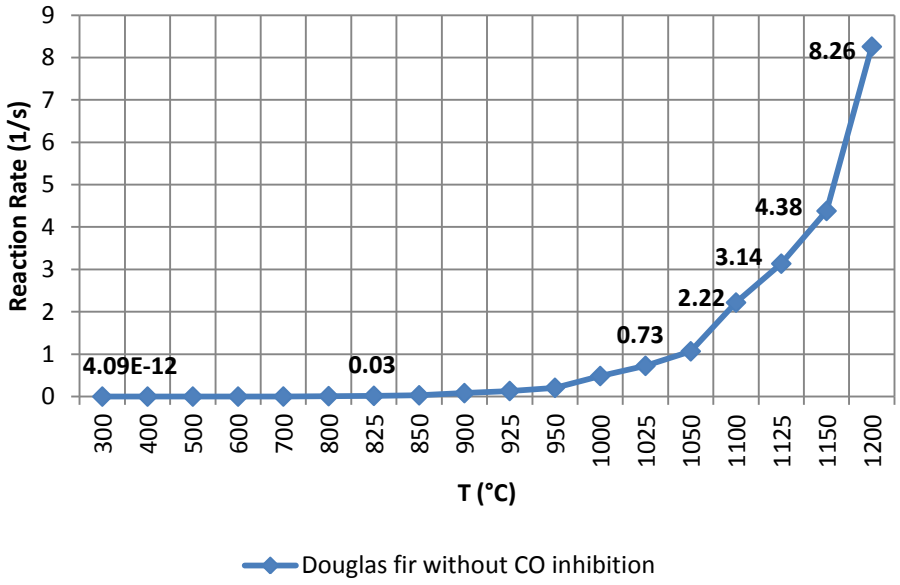

Figure 2.3 *Boudouard reaction rate on the function of temperature for douglas fir char (own elaboration based on the calculations of Appendix 1).*

The different orders of magnitude in figures 2.2 and 2.3 mean that biomasses (even two different kind of wood) may have very different reaction rates. Basu (2013) does not give any information for example about the porosity of the biomasses which affects greatly the reaction rates. Although bamboo is very similar to douglas fir, unfortunately straight conclusions to their similarity in reaction rates cannot be done based on this

information. Hence more investigation e.g. on porosity and reaction rates of bamboo is needed in the future.

2.5 Tar Production

Many definitions for gasifier tars can be found in the literature:

1) Tars are defined as the organic material that condenses on a filter at the temperature of 80-100 °C and that consists of creosotes and polynuclear aromatics. (Das 1998, p.5)
2) Tars are the organics, produced under thermal or partial-oxidation regimes (gasification) of any organic material and that are generally assumed to be likely aromatic. (Milne et al. 1998, p. v)
3) Tar is thick, black, highly viscous liquid that condenses in the low-temperature zones of the gasifier. (Basu 2013, p.97)

Also, according to Basu, The International Energy Agency (IEA) Bioenergy Agreement, the US Department of Energy (DOE), and the DGXVII of the European Commission agreed to identify as tar all the components of the synthesis gas that have a molecular weight higher than that of benzene. (Basu 2013, p.177) Yet none of these definitions is very extensive because the nature of the tar depends on the biomass, the gasifier geometries, configurations, temperature profiles, residence times and bed materials. (Milne et al 1998, p. 27)

The three main constituents of biomasses are cellulose, hemicellulose and lignin. Over 70 % of the biomasses' weight is volatile matter which pyrolyzes in elevated temperatures and can thus form tars if it condenses. Cellulose and hemicellulose are the main sources of volatile matter in biomass as explained in table 2.1.

Table 2.1 *Tar producing components in biomass (adapted from Basu 2013, p.74-75).*

	Decomposition Temperature °C	Gasification yield	
Hemicellulose	150-350	Volatiles, Non-condensable gases	Unstable components
Cellulose	275-350	Volatiles, Condensable vapor	Levoglucosan (tars)
Lignin	250-500	Char	Aromatics, phenols (tars)

Most tars are produced by cellulose and lignin whereas hemicellulose produces non-condensable, unstable gases that form no harm in a gasifier. Lignin consists of aromatic hydrocarbons including benzene rings which are really hard to break due to several

double bounds and electron delocalization. That is why many troublesome tar compounds (polycyclic aromatic hydrocarbons (PAH) such as furans and phenols) originate from lignin.

Tars can be divided into 4 categories: primary, secondary, tertiary and condensed tertiary products. Levoglucosan is one of the primary tars and it vaporizes above 350 °C. The PAH-compounds belong to the condensed tertiary products and form the most cumbersome tars. (Evans & Milne 1987, cited in Milne et al. 1998, p. 6.)

The presence of different tar yields depends on the gasifier conditions. For example the primary products are expected to be destroyed before the tertiary products appear in the gasifier as seen in figure 2.4. Thus primary and tertiary tars in the same tar sample would indicate process upsets or non-uniform conditions and therefore understanding the tar behavior can help optimizing the reactor performance. (Milne et al. 1998, p. 6-7.)

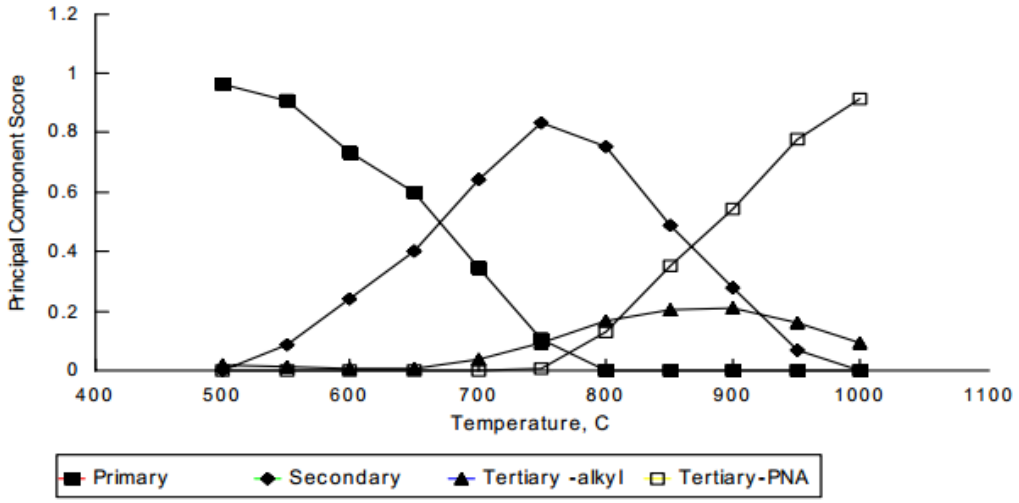

Figure 2.4 *Different tar yields as a function of temperature (Milne & al. 1998, p.7)*

It has been proven technically and scientifically that updraft gasifiers produce more tars than fluidized bed gasifiers and fluidized bed more than downdraft gasifiers. (Milne et al 1998, p. 13) The updrafts have large amounts of primary tars and some degree of secondary tars whereas a downdraft gasifier mainly produces tertiary tars. Although the amount of tars in downdraft gasifier is a lot lower than that of updraft gasifier (roughly defined 1 g/Nm^3 vs. 100 g/Nm^3), the nature of tars is a lot more cumbersome. (Milne et al 1998, p. 21.) The dilemma is that with higher temperature it is possible to reach greater efficiency but it also leads to more refractory tars. (Milne et al. 1998, p.10)

If the syngas is used in an internal combustion engine, the gas has to be well cleaned. Otherwise the condensed creosotes and polynuclear aromatics might be very difficult to remove from pipes and engine parts and the engine might get stuck. (Das 1998, p.5.) The cleaning is expensive and rather difficult to carry out. This is probably the biggest reason why gasification is not yet a widely used conversion technique for electricity production.

2.6 Factors Affecting the Gasification Process Stability

Controlling the gasification process is not an easy task. Obtaining a stable production of good quality synthesis gas requires deep knowledge of different factors affecting the process. It is also important to be able to measure and adjust these different factors.

Next the effect of a few different factors is discussed in more detail. These are the feedstock moisture, the equivalence ratio (ER) and the pyrolysis conditions.

2.6.1 Feedstock Moisture Content

The feedstock quality, especially its moisture content, is a key player in a successful gasification process. Biomasses always include a high percentage of moisture because of their nature: the plant sucks water from the ground and transfers it all the way to the leaves where the photosynthesis takes place. That is why there is a difference in the moisture content of different parts of the plant (stem vs. leaves).

In elevated temperatures of the gasifier the moisture is evaporated and it becomes steam. This steam works as a gasifier agent reacting with volatiles and char producing syngas and taking part in the water-gas shift reaction (equation 2.7) that produces hydrogen. However, if excessively moist feedstock is fed into the gasifier, a lot of energy is needed to evaporate the extra water. This energy is not recoverable which makes the use of very humid feedstock unfavorable in the gasifiers. (FAO 1986, p. 28; Reed & Das 1988, p. 18) The moisture content should also be as constant as possible throughout the biomass. Otherwise the process becomes harder to control, the composition of the synthesis gas starts changing and its heating value lowers.

More information about the feedstock quality and its effects can be found in chapter 3.

2.6.2 The Equivalence Ratio

Equivalence ratio (ER) means the actual air ratio used in a gasification process over the amount of stoichiometric air as seen in the equation 2.9. It can also be defined using air-fuel-ratios (A=mass flow of the air, F=mass flow of the fuel). Stoichiometric means the amount of air that is needed for complete combustion of the fuel.

$$\mathrm{ER} = \frac{\text{Actual air}}{\text{Stoichiometric air}} = \frac{\left(\frac{\mathrm{A}}{\mathrm{F}}\right)_{\text{Actual}}}{\left(\frac{\mathrm{A}}{\mathrm{F}}\right)_{\text{Stoichiometric}}} \tag{2.9}$$

The ER is one of the most important factors defining the gasifier operation because the amount of air is related to the amount of oxygen. Oxygen is needed for the exothermic oxidation reactions (combustion) that provide heat for the endothermic gasification reactions and for the feedstock and gasification medium to raise to the reaction temperatures. Also the overall temperature of the gasifier depends on the amount of air used. In

gasifiers burning is supposed to be incomplete and the ER < 1 meaning that only a fraction of the stoichiometric air should be used. When the ER > 1 a stoichiometric or an excess amount of air is present and burning is more complete. This is the case in combustion. (Basu 2013, p.278.)

In gasification processes the optimum value for the ER is between 0.19-0.43 depending on the gasifier and the feedstock among other things. (Gunarathne 2012, p. 17) According to the experiments of Gunarathne (2012) the optimum equivalence ratios for different throat diameters of a downdraft gasifier were 0.356-0.360 when wood was gasified. Other researchers mentioned in his study have obtained similar results for the ER varying from 0.210 to 0.388. Reed & Das (1988) suggest that the most favorable ER for a downdraft gasifier is around 0.25. That is when the majority of char is converted to gas. If too little oxygen is provided, some of the char is not converted and it will start to pile up at the bottom of the gasifier and the syngas will have a lower heating value. Then again if the ER is too high and there is too much oxygen present, part of the syngas is burned which increases the amount of combustion yields such as CO_2 and H_2O and decreases the wanted CO and H_2. Hence the heating value will be lower again. Also the temperature of the gasifier rises quickly due to the greater extent of the exothermic combustion reaction (Reed & Das 1988, p.25; Basu 2013, p.196.)

The following figure 2.5 shows two important relations of the ER. The carbon conversion efficiency and the bed temperature are illustrated on the function of the ER in a fluidized bed gasifier of wood. In this case the conversion efficiency gets its highest value when ER≈0.26 but starts declining after that. This means that the carbon of the fuel turns into carbonaceous products most effectively. The bed temperature also rises within the ER because with more oxygen there will be more combustion and thus more heat released.

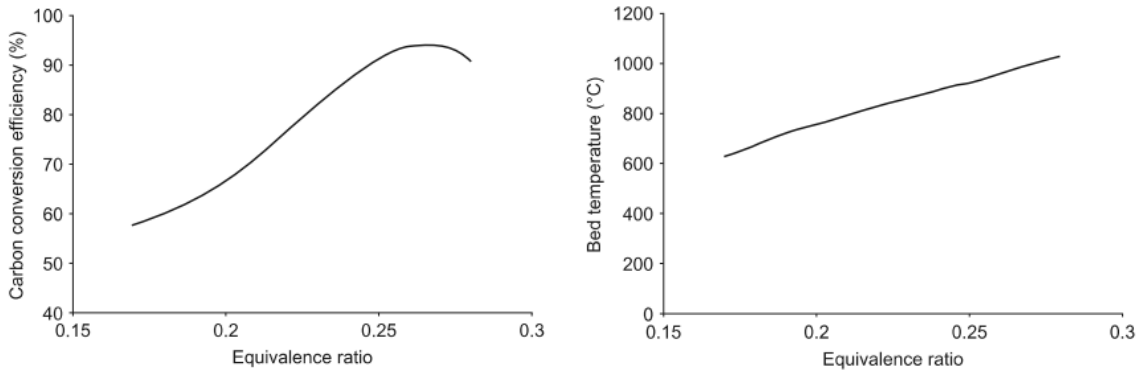

Figure 2.5 *The carbon conversion efficiency and the bed temperature on the function of the ER in a fluidized bed gasifier for wood (adapted from Basu 2013, p. 278-279).*

The Equivalent Ratio (ER) is an important factor also concerning tar yields. The higher ER allows more oxygen to react with the volatiles and less tar is formed. Also higher temperature helps tars to decompose. The disadvantage of high ER rates is that the heating value of the synthesis gas is decreased due to nitrogen dilution from the air used. (Basu 2013, p. 106.) More information about tars can be found in section 2.5.

There are two possible ways to maintain an optimal equivalence ratio. Depending on the gasifier equipment either the mass flow of the feedstock or the air flow can be modified. In the test runs carried out for this study only the variation of the air flow by adjusting the blower was possible.

2.6.3 Pyrolysis Conditions

Different heating rates and residence times used in pyrolysis affect greatly the pyrolysis yield and thus also the final gasification product. Low temperature (350-400 °C), slow heating rate (0.01-2.0 °C/s), long residence time pyrolysis is often called carbonization because it maximizes the production of char and non-condensable gases (H_2, CO, CO_2). Char is primarily carbon but it can also contain some oxygen and hydrogen. Then again flash pyrolysis happens in high temperature (500-600 °C) and in short residence time with high heating rate and it maximizes the production of condensable oils. (Kerlero de Rosbo & de Bussy 2012, p.26; Basu 2013, p.77). This bio-oil is produced by rapidly and simultaneously depolymerizing and fragmenting cellulose, hemicellulose and lignin components of biomass. (Basu 2013, p.70) The pyrolysis yield also depends on the chemical characteristics of the biomass and the final temperature reached in the reactor.

The size of the feedstock obviously also has an effect on the rate of the pyrolysis. Bigger particles require longer residence times and thus are more likely to form charcoal and non-condensable gases. Smaller particles are faster pyrolyzed and hence form more tars and oils. (Kerlero de Rosbo & de Bussy 2012, p.26). In this study the production of char and non-condensable gases is wanted so slow heating-rate and long residence times should be applied in pyrolysis and hence the size of the feedstock should not be too small.

2.7 The Principal Gasifier Technologies

The different names of the gasifiers reflect the ways the fuel and the air are flowing inside the gasifier. Heat can be supplied by direct combustion of the pyrolysis gases (downdraft gasifier), by combustion of charcoal (updraft gasifier) or by the combination of these two (fluidized bed gasifier). (Reed & Gaur 2001, p.1-10.) Both downdraft and updraft gasifiers represent fixed bed technologies. Some important characteristics of these three technologies are listed in table 2.2 and discussed briefly in the next sections.

Table 2.2 *Comparison of some characteristics of the gasifiers (Basu 2013)*

	Downdraft	**Updraft**	**Fluidized Bed**
Application size range	20 kW-2 MW	2-30 MW	3-100 MW
Tars	0.015-3.0 g/Nm^3	30-150 g/Nm^3	10 g/Nm^3
Gas exit temperature	700 °C	200-400 °C	800-1000 °C
Reaction zone temperature	1000 °C	1000 °C	800-1000 °C
Cold gas efficiency	80 %	80 %	89 %

2.7.1 Fixed Bed Downdraft

The downdraft gasifier is also called co-flow or tar burning gasifier. The feedstock enters from the top of the gasifier, whereas the air/oxygen is fed into the ”throat” through various nozzles as seen in figure 2.6. The fuel and air are ignited in the reaction zone and the flame generates pyrolysis gases (volatiles) that then burn intensively leaving 5-15 % of charcoal. The charcoal reacts with down flowing combustion gases and more CO and H_2 are produced. At the same time the temperature is being reduced from 800-1200 °C to below 800 °C because of the endothermic reactions. In the end char ash passes into the ash disposal. (Reed & Gaur 2001, p.1-12.)

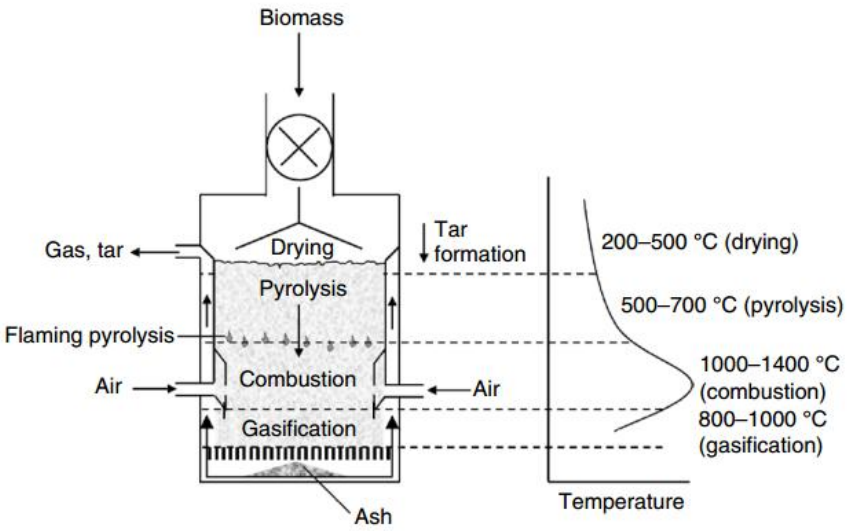

Figure 2.6 *A downdraft gasifier and its temperature profile (Basu 2013)*

The absolute advantage of the downdraft gasifier is that 99-99.9 % of tars are cracked because they pass through the high temperature zone. Thus the synthesis gas is rather clean and can be used e.g. in combustion engines. The downdraft gasifier is well tested technology since more than a million vehicles ran satisfactorily using it during the World War II. However, there are also a few disadvantages to mention. The entering feedstock should be well pre-dried because the maximum moisture content shall only be 20 % of the biomass’ weight. Otherwise the temperature inside will decline and the production of tars increases. The synthesis gas leaves the gasifier at the temperature of approximately 700 °C which is too hot for instance for engines. Thus a heat exchanger has to be used and the heat must be wasted or redirected for drying of the moist feedstock, heating up the gasifier or other purposes. (Reed & Gaur 2001, p.1-13.)

2.7.2 Fixed Bed Updraft

The updraft gasifier is also a called counter-flow or a char-burning gasifier. It is the oldest and also simplest model of gasifier. The feedstock enters from the top and it is flowing downwards while the air/oxygen is fed from the bottom and together with flue gases

they flow upwards. That is where the name counter-flow is derived from. The feedstock is dried by the up flowing flue gases and after that it gets pyrolyzed by the gasification gases producing vapor and charcoal. The down flowing charcoal reacts with up flowing CO_2 and H_2O derived from the combustion zone and CO and H_2 are produced. The charcoal burns with air/oxygen in the oxidation (combustion) zone at high temperatures as seen in the figure 2.7. Finally ash falls down through the grate into the ash disposal. (Reed & Gaur 2001, p.1-11.)

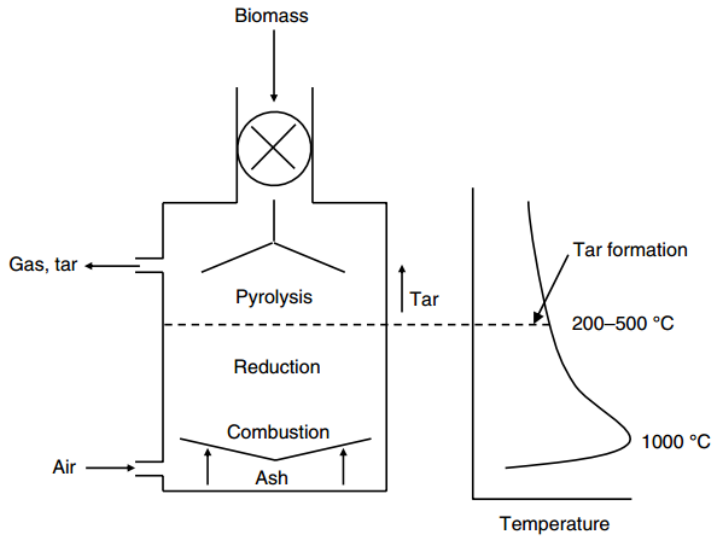

Figure 2.7 *An updraft gasifier and its temperature profile (Basu 2013)*

The advantages of an updraft gasifier are the simple structure and the ability to gasify materials with high water and inorganic content. Then again primary tars are produced in the temperature range of 200-500 °C (see figure 2.7) from where they travel up to the cooler zones and no cracking will occur. That is why the synthesis gas contains up to 10-20 % of tars that are hazardous for any engine, turbine or synthesis application. (Reed & Gaur 2001, p.1-12; Basu 2013, p.109.)

2.7.3 Fluidized Bed

In a fluidized bed gasifier (bubbling or circulating) the air enters from the bottom with a high velocity and the feedstock from the top or side as seen in figure 2.8. With a certain speed a point is reached where the solid fuel particles are carried with the gas. In other words they start floating or circulating in the air. (Higman & Van Der Burgt 2008, p.98.) Sometimes an inert material (such as sand or dolomite) is used to improve the heat transfer of the feedstock passing through the bed and sometimes the fuel itself forms the bed. There is a huge variety of different fluidized bed gasifiers depending on the degree and manner of levitation, the particle size and the end use of the gas. (Reed & Gaur 2001, p.1-17). The fluidized beds usually operate between 800-1000 °C to avoid ash agglomeration. (Basu 2013, p.216)

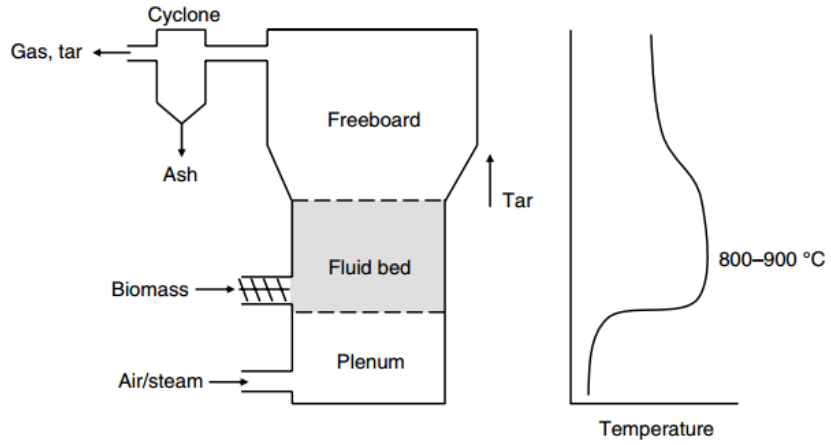

Figure 2.8 *A fluidized bed gasifier and its temperature profile (Basu 2013)*

In all fluidized bed gasifiers the gasifying agent comes into immediate contact with fresh biomass particles and with the char particles (=biomass that has already been converted into char inside the gasifier). Fresh biomass dries quickly and starts undergoing pyrolysis and at the same time the entering oxygen burns the tars that are being released. When the oxygen gets in contact with the char particles, the char starts to burn. Any tar that is being released moves up with the product gas and thus does not get burned. For this reason fluidized bed gasifiers produce an average amount of tars. (Basu 2013, p. 192.)

Fluidized beds have higher throughputs than fixed bed gasifiers and also the heat transfer rates are higher because of a good solid-gas mixing. They are very fuel flexible and can handle high concentrations of water. Then again the formation of tars might form a problem in some applications and the handling the fluidized bed is more complex so they are mainly used in larger, industrial installations. (Reed & Gaur 2001, p.1-17, 1-18.)

2.8 Safety and Environmental Aspects

Gasification and gasifiers may cause hazards for the user and for the environment. There is a possibility for intoxication, fires, explosions and environment contamination. The next sections will discuss these hazards in more detail.

2.8.1 Toxic Hazards

Carbon monoxide (CO) and hydrogen (H_2) form the principal constituents of the synthesis gas (if inert nitrogen is not considered). They are both dangerous substances but in a different way. H_2 is not poisonous but it forms a very inflammable mix with air. When it burns, the flame is almost invisible and so hot that it is capable of melting most materials. (FIOH 2011) Carbon monoxide then again is extremely toxic for humans because of its ability to tie up with the hemoglobin of the blood and thus prevent the transport of oxygen to the cells. Already small amounts may cause headache, nausea,

unconsciousness and even death. CO is odorless and tasteless which makes it difficult to detect. (FAO 1986, p. 45; Reed & Das 1988, p. 119.)

Normally gasifiers operate under suction at negative pressure. If any leakage occurs during the operation, the synthesis gas will not escape from the gasifier but the surrounding air will flow into the gasifier. However, during the start-up and closing-down the situation is different. Before starting up the gasifier has to be ventilated so that no gases are left inside from the previous run. These gases are released into the surroundings of the gasifier. If it is situated in an enclosed room, the user is exposed to the dangers of CO. Also when the engine is started on synthesis gas, leaks occur. These gas releases can be avoided by installing a burner at the fan outlet and turning on the engine by using liquid fuel. (FAO 1986, p.45.) An easy way to avoid harms caused by CO is to install a CO detector near the gasifier that alarms every time that carbon monoxide is detected.

When the gasifier is shut off, the hot fuel keeps on pyrolyzing and producing CO. Since suction is no longer present, the pressure inside the gasifier builds up and the gases may start leaking out. That is why it is recommended to build the gasifier installations in an open air or well ventilated space. (FAO 1986, p.45; Reed & Das 1988, p.121.)

2.8.2 Fire and Explosion Hazards

Gasification can cause fires and explosions for a few reasons. The equipment gets really hot during the processes because of elevated temperatures inside the gasifier. This can cause flaming of materials if they get in touch with the gasifier. This can be the case for example when refilling the gasifier and pieces of biomass spill over the hopper. A good insulation of the hot parts is thus recommended. (FAO 1986, p. 45.)

When the gasifier is refilled, the lid of the hopper must be opened. There is a risk that gases inside the hopper flash and sparks fly out of the gasifier which may cause a fire if burning material is stored nearby. When the lid is opened, air enters the gasifier. It might form an explosive mixture with the pyrolytic gases. The explosions are usually relatively small and harmless but still attention must be paid. Safety valves or double sluice filling systems can be used to lower the pressure of the gasifier caused by the explosion and thus secure safe operation. (FAO 1986, p. 46; Reed & Das 1988, p. 122.)

If air leaks into the cold gasifier and it is immediately ignited, and explosion will occur. That is why ventilating the gasifier before start-up is obligatory. The gas produced during the start-up includes a lot of tars because the temperature of the gasifier has not yet risen and the cracking of tars is incomplete. That is why the gas should not be passed through the whole filter section because it will block the filters. The filters might still contain air and once the synthesis gas is passed through the filters and ignited at the fan outlet (where the engine is) a backfire can occur. It would be recommendable to use a water lock or a flame arrester to prevent the backfiring phenomenon. (FAO 1986, p. 47; Reed & Das 1988, p. 122.)

2.8.3 Environmental Hazards

Gasification has an effect on the environment. When different biomasses are used as fuels, it has to be done sustainably especially if gasifiers come into wide use again (as was the case during the World War II). The use of bamboo (or any biomass) must be planned well using efficient forest management. Excessive use of biomass will remove the nutrients from the soil and expose the lands to erosion. (Reed & Das 1988, p. 123.)

Gasifiers connected with an internal combustion engine produce ashes, particulates, tars and exhaust gases. The ashes are not harmful for the environment and they can be reused as fertilizers or in road building. Then again the tar containing condensable gases do have unfavorable effects on the environment. For example the polyaromatic hydrocarbons can contaminate the soil and ground water. Tarry and phenolic constituents need special waste handling which is difficult and expensive to carry out. That is why gasifiers should be designed so that a minimum amount of these substances is produced.

Engines produce the following flue gases: Carbon dioxide (CO_2), oxygen (O_2), carbon monoxide (CO), organic hydrocarbons (C_xH_y), nitrogen oxides (NO_x), nitrogen (N_2), steam (H_2O) and trace elements of organic and inorganic substances. From these gases CO_2 and steam participate in the greenhouse effect. However, the amounts of the gases are lower than those of diesel engines or conventional combustion and thus produce no severe problem for the environment. (Kerlero de Rosbo & de Bussy 2012, p.43.) The synthesis gas does not include solid, unburned matter and that is why the flue gases do not contain soot or other solid particles. The amount of SO_x depends on the sulfur content of the fuel. (Raiko et al. 2002, p. 620.) Bamboo only has a small fraction of sulfur so the flue gases are rather clean.

3. THE FEEDSTOCK QUALITIES

It is sometimes stated that one single gasifier is suitable for gasifying any kind of biomass. This is not exactly true because every biomass is different. Therefore the gasifier has to be built to meet the fuel's characteristics and thus it is extremely important to know the qualities of the utilized biomass.

The most important fuel qualities affecting gasification are its energy and moisture content, the amount of volatile matter and fixed carbon, ash content, slagging characteristics, bulk density and size distribution. The following sections 3.1-3.6 discuss these qualities in more detail. The qualities of bamboo of Huatusco, Veracruz are compared with other values found in the literature. In the end, the section 3.7 concentrates on the pre-processing of bamboo to make it a suitable gasifier feedstock.

3.1 Characteristics of Bamboo

Bamboo is known as the world's largest grass plant and it belongs to the family of Poaceae (also called Gramineaes) and the subfamily of Bambusoideae. It is very woody and grows rapidly reaching an incredible pace of 10-20 cm per day making it an intriguing option for a gasification feedstock. (Bambuver A.C. 2013a, p. 5.) Bamboos mostly grow in the tropical and subtropical zones occupying 14 millions of hectares of the world. 80 % of the bamboo is found in the South and South East Asia, mostly in China, India and Myanmar. However, there are many species growing in the continents of Africa and America as well: in Mexico 8 genera and 39 species can be found (Castañeda 2004, p.9.)

The bamboo plantations, which are being discussed in this thesis, are located in Mexico, in the municipality of Huatusco, Veracruz. A nonprofit organization called Bambuver A.C. is leading a local development project aiming at reforestation, improving regional industrial growth, agriculture technologies, sustainable development and employment creation. (Bambuver A.C. 2014.)

The plantations consist of 200 hectares of different bamboo species of which 40 hectares are for producing feedstock for gasification. (IIE 2012a, p. 1) The rest can be used for example for house building, door mats, bridges, floors, furniture, crafts, paper pulp, textile fibers and carbon. Many bamboo species are also edible (Bambuver A.C. 2013a, p. 3).

There is a huge variety of different bamboos but not all of them are suitable for energy production. The main interest lies on the species listed in table 3.1 below.

Table 3.1 *The bamboo species examined for gasification. (IIE 2012a, p.1)*

Scientific Name	Common Name	Availability (hectares)
Bambusa Old Hamii Munro	Oldhamii	18
Bambusa Vulgaris Vitata	Yellow Vulgaris	12
Bambusa Vulgaris Schrader	Green Vulgaris	6
Dendrocalamus Strictus	Strictus	2
Dendrocalamus Asper	Asper	2
	Σ	**40**

All of these species are woody and fast growing. (Bambuver A.C. 2013a, p.6) According to the investigation of Castañeda (2004) the new Oldhamii-culms are capable of accumulating 32,200 kg of biomass per hectare in a year which equals to approximately 3500 kg/day considering the total 40 hectares of field. It is also worth mentioning that the plantation of Huatusco Veracruz is one of the most productive bamboo plantations in the world. (Castañeda 2004, p.34.)

In comparison, Eucalyptus is known as one of the fastest growing hardwoods in the world. Nevertheless, according to Gonzalez et al. (2011) the reported average biomass production rate was only 22,400 kg/ha/year. Thus bamboo seems to be even a lot faster growing plant than eucalyptus.

3.1.1 Physiochemical Characteristics

Bamboo culm consists of jointed intersections that are called nodes and internodes. Node is the solid, cross sectional part that devides two internodes from each other (see figure 3.1). The internode is always hollow. Culms form the vascular system that transports water and nutrients through the bamboo. Bamboo also has branches that grow from the nodes and leaves that grow at the end of branches as illustrated in the figure 3.1. (Liese 1984, p.1.)

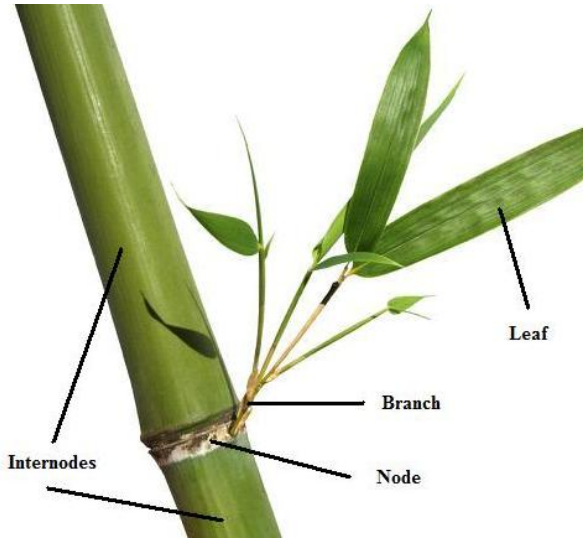

Figure 3.1 *The parts of a bamboo culm. (Schlau 2009)*

The outer part of the culm has two epidermal cell layers whereas the inner part is thicker and highly lignified. The three main constituents of bamboo culms are cellulose, hemicellulose and lignin and thus it forms a part of the ligno-cellulosic biomasses. The rest consists of resins, tannins, waxes and inorganic salts. The composition varies throughout the culm and it also depends on the species, the conditions of growth and the age of the bamboo. During the first year the composition of bamboo is changing but once the plant has matured and the soft and fragile sprout becomes hard and strong, the composition remains constant. (Liese 1984, p.6.)

The chemical constituents of bamboo (Bambusa Vulgaris Vitata) and wood (Pseudotsuga Menziesii = Douglas fir) are listed in table 3.2 below. Although bamboo is classified as a grass plant, it is justifiable to state that it is closer to timber due to its high cellulose and lignin content, as seen in the table. Most herbaeous biomasses have a really high ash content (> 10 w-%) whereas douglas fir only has 0.2 % ash of its weight. Bamboo is placed between those two having an ash content of 2-3 w-%. Ash is an important factor for gasification fuels because it might cause harmful slagging in a downdraft gasifier.

Table 3.2 *The chemical composition of bamboo compared with wood. The numbers are weight-% on a dry basis.*

Species	Cellulose	Pentosans	Lignin	Benzene	Hot Water	1% NaOH	Ash	Silica	Ether
Bambusa Vulgaris Vitata[1]	**66.5**	21.1	**26.9**	4.1	5.1	27.9	2.4	1.5	n/r
Pseudotsuga Menziesii[2]	**66**	8	**27**	4	4	13	0.2	n/r	1.3

[1]Liese 1984, p.7; [2]Pettersen 1985, p.79

N/r in the table means that some of the components were not reported within these results.

3.2 The Feedstock Moisture

The moisture content of feedstock affects greatly the gasification process. More information about the effects can be found in subsection 2.6.1 so it will not be repeated here. The next subsection 3.2.1 concentrates on measuring the humidity of bamboo.

3.2.1 Measuring the Moisture Content of Bamboo

The moisture content of biomass is rather simple to find out. It is based on the ISO 589:2008 method (Hard coal – Determination of Total Moisture) or on the American standard ASTM D2016-74 (1983) (Methods of Test for Moisture Content of Wood). Also other methods exist.

The size of the examined samples depends on the accuracy of the scale. When the accuracy is 0.01 g two samples of biomass of 30-100 g are weighted. If the accuracy is lower, 0.1 g, two samples of 200-400 g are weighted. The samples should be put into containers that do not absorb humidity and that support heat. After this the samples are placed into a hot air oven and heated up to 105 °C (Alakangas 2000, p.27; Raiko 2002, p.121) or 110 °C (Reed & Das 1988, p.10). Common for all the methods is that the samples are kept in the oven for about 15-20 hours until their weight is constant. That means that all the water has evaporated. If higher temperatures are used, the outer layers of biomass may start to pyrolyze before the other parts are properly dried. (Reed & Das 1988, p. 19) The biomass needs to be weighed immediately after taking the sample out of the oven because the humidity of the air quickly gets absorbed into the sample which ruins the results.

The moisture content on a dry basis can be calculated as follows:

$$\text{Moisture Content } \% = \frac{\text{Weight}_{\text{Green}} - \text{Weight}_{\text{Dry}}}{\text{Weight}_{\text{Dry}}} * 100\ \% \tag{3.1}$$

In the equation (3.1) $\text{Weight}_{\text{Green}}$ means the weight of the biomass as it is before heating in the oven. $\text{Weight}_{\text{Dry}}$ then again is the biomass weight when all the water has evaporated. (Alakangas 2000, p.26.)

The humidity of six different bamboo samples was examined for this work. The method described in Alakangas (2000) was applied for the measurements. When the green weights and dry weights had been measured, the equation (3.1) was used to calculate the moisture contents on the oven-dry basis. The results are listed in table 3.3. More experiments on these bamboo samples are done later in chapter 6.

Table 3.3 *The measured moisture contents of bamboo (own elaboration).*

	Huatusco Bamboo	**Moisture Content**
Measurement 1	Bambusa Old Hamii Munro	15.19 %
	Bambusa Old Hamii Munro	15.06 %
Measurement 2	Bambusa Vulgaris Vitata	14.73 %
	Bambusa Vulgaris Vitata	13.38 %
Measurement 3	Bambusa Vulgaris Vitata	13.42 %
	Bambusa Vulgaris Vitata	13.42 %

It can be observed that all the samples are suitable for being gasified in a downdraft gasifier where moisture content generally should be lower than 20 %. These bamboo chips had been cut 2-4 days before carrying out the measurements and they had already been oven-dried by the staff of Bambuver A.C. (about 24 hours in a 60-degree oven). Fresh bamboo normally has a moisture content of 27-45 % depending on the species, age and the season so pre-drying before gasification is necessary. (IIE 2012a; IIE 2012b)

3.3 Proximate Analysis

Raiko et al. (2002) explain that a solid fuel consists roughly of three parts: burning matter, ash and water. Both ash and water are lowering the quality of the fuel whereas burning matter, as its name says, is important for the fuel quality.

Proximate analysis is used for determining the burning matter (volatile matter and fixed carbon) and the ash content of the fuel. (Reed & Das 1988, p.10) An analysis for bamboo can be seen in table 3.4 below.

Table 3.4 *The proximate analysis for bamboo, coal, wood and reed canary grass (dry basis).*

Biomass	Volatile Matter w-%	Ash w-%	Fixed Carbon w-%
Bambusa Old Hamii Munro [1]	78.80	3.28	17.9
Bambusa Vulgaris Vitata[1]	76.70	5.14	18.1
Bambusa Vulgaris Schrader[1]	75.89	4.76	19.3
Dendrocalamus Strictus [1]	79.07	3.41	17.5
Dendrocalamus Asper [1]	77.49	3.25	19.2
Pittsburg Seam Coal[2]	33.90	10.30	55.80
Pseudotsuga menziesii (Wood)[2]	86.20	0.10	13.70
Phalaris arundinacea (Reed Canarygrass)[3]	74.00	5.50	20.50

[1] IIE 2012a; [2] Reed & Das 1988, p.11; [3] Alakangas 2000, p. 105

The values are weight percents measured in the Combustible Analysis Laboratories at the Institute of Electrical Research, Cuernavaca, Mexico using the following ASTM standards: D3174 (ash content), D3175 (volatile matter) and D3172 (fixed carbon). (IIE 2012a) In the same table also the proximate analysis data for Pittsburg seam coal, Douglas fir (Pseudotsuga menziesii) and Reed canarygrass (Phalaris arundinacea) are represented. The elemental analysis shows that the values of bamboo are between those of wood and grass but far from the values of coal. The next subsection discuss some qualities in more detail.

3.3.1 Volatile Matter Content

Bamboo, as biomasses in general, includes a high amount of volatile matter as seen in table 3.4. Typically the values vary between 70 and 86 w-%. Because of these volatiles a major part of the biomass fuel is vaporized during the pyrolysis. Therefore, the amount of the volatile matter affects the thermal decomposition and combustion behavior of solid fuels. (Van Loo & Koppejan 2008, p.41.) For example Douglas fir of table 3.4 would be expected to decompose faster than any of the bamboo species.

The volatiles may also turn into harmful tars depending on the process temperature and the gasifier design. The rule of thumb is that the fuels that include more than 10 % of volatile matter should be gasified using the downdraft technology to avoid the formation of tars. (FAO 1986, p. 28)

3.3.2 Ash Content

Ash is the mineral content of the fuel that remains in the gasifier after complete combustion. Ash-forming elements are present in biomass as salts that are bound in the carbon structure (=inherent ash) or they might drift into the gasifier with dirt and clay due to harvesting or transportation (=entrained ash). (Van Loo & Koppejan 2008, p. 34.)

Ashes can cause a lot of problems in the gasifiers. The compounds may melt and agglomerate producing clinker and causing slagging. This slag has to be removed which increases the need for workforce, causes a break for operation and thus increases costs. Slagging can partly or completely block the gasifier and inhibit the down flow of the fuel causing a pressure drop and excessive tar formation. It can also lead to air-channeling which may produce a risk of explosion. (FAO 1986, p. 29.)

The occurrence of slagging depends on the ash content of the fuel, the melting characteristics of the ash and the temperature profile of the gasifier. Usually slagging causes no troubles if the ash content of the fuel is lower than 5-6 %. (FAO 1986, p. 29.) As seen in tables 3.2 and 3.4 bamboo's ash content is lower than that.

The ash melting tests for Huatusco bamboo were carried out in a laboratory called Sylab, in France. The deformation temperatures and the fusion temperatures can be seen in table 3.5. As seen in subsection 2.7.1 in figure 2.6 (Downdraft gasifier) the temperatures in the combustion zone can rise up to 1400 °C. Thanks to bamboo's low ash content this should not be a major problem but still the ash melting needs to be looked out for. The Indian bamboo serves as a comparison for the Huatusco species in the following table.

Table 3.5 *Ash deformation and fusion temperatures of Mexican and Indian Bamboo.*

	Deformation Temperature	**Fusion Temperature**
Huatusco Bamboo[1]	826-1227 °C	963-1327 °C
Indian Bamboo[2]	1000-1100 °C	1100 °C

[1] Sylab 2014; [2] Ganesh 2003

3.4 Ultimate Analysis

The ultimate analysis gives the chemical composition of the fuel. The burning matter includes mainly carbon (C), hydrogen (H), nitrogen (N), sulphur (S) and oxygen (O). For energy production the most important substances are carbon and hydrogen because

of their high heating values whereas nitrogen and sulphur form compounds (SO_x, NO_x) that are harmful e.g. for nature and the equipment. (Raiko et al. 2002, p.124.)

An ultimate analysis for bamboo can be seen in table 3.6. The analysis was carried out in the Combustible Analysis Laboratories at the Institute of Electrical Research, Cuernavaca, Mexico using the following ASTM standards: D5373 for determination of carbon, hydrogen and nitrogen content, D4239 for determination of sulfur and the amount of oxygen was obtained by balance calculations. (IIE 2012a) The ultimate analyses for Pittsburg seam coal, Douglas fir and Green canary grass are also represented.

Table 3.6 *The ultimate analysis for different bamboo species and fuels (dry basis).*

Biomass	**C** **w-%**	**H** **w-%**	**O** **w-%**	**N** **w-%**	**S** **w-%**
Bambusa Old Hamii Munro[1]	46.70	6.09	43.80	n/d	0.05
Bambusa Vulgaris Vitata[1]	45.90	5.81	43.10	n/d	0.05
Bambusa Vulgaris Schrader[1]	46.00	5.95	43.10	0.15	0.05
Dendrocalamus Strictus [1]	46.70	5.91	43.80	0.12	0.05
Dendrocalamus Asper[1]	47.00	5.93	43.80	n/d	0.05
Pittsburg Seam Coal[2]	75.50	5.00	4.90	1.20	3.10
Pseudotsuga Menziesii (Wood)[2]	52.30	6.30	40.50	0.10	0.00
Phalaris Arundinacea (Reed canarygrass)[3]	44.60	5.55	40.11	0.00	0.22

[1] IIE 2012a; [2] Reed & Das 1988, p.13; [3] Alakangas 2000, p. 106

N/d in the table means that no nitrogen was detected in a few samples. The table shows that wood and grass properties are fairly close to those of bamboo but coal is in its own category. The percentage of sulfur in bamboo is very low which is good because it does not produce that many acid components in gasification. In coal burning applications corrosion might form a problem because of higher sulfur content of coal. Hydrogen in all of the fuels is within the same range but the amount of carbon varies. The difference in carbon causes the differences in the feedstock's heating values as seen in the next section.

3.5 Energy Content

The energy content of the fuel, that is released when it is completely burnt, is called the heating value of the fuel. For gaseous and liquid substances the heating value (also known as calorific value or energy value) is easy to calculate through the reaction enthalpies of different components in combustion reactions. However, for solid matters the only way to determine an *accurate* heating value is by letting the fuel react with oxygen in a bomb calorimeter and measure the heat released. That is because solid fuels usually include oxygen that forms different products when it reacts with the burning

matter and it is not possible to know the exact amount of these compounds. However, different equations for calculating the heating value also exist but the results may differ significantly from the measured ones. (Raiko et al. 2002, p.52.)

Fuels include a certain amount of humidity (H_2O). Depending on the burning conditions this water might appear as liquid or as vapor. It has an effect on the reaction enthalpy because the vaporization of water requires energy (the latent heat). (Raiko et al. 2002, p.52.) **Higher heating value (HHV)** is a measure of energy content of biomass without any "free" water (=oven-dry basis). Still, the biomass contains chemically bound water and water that will arise as a result of combustion reactions. The HHV includes the latent heat of the water and that is why the result is higher. (Rosillo-Calle et al. 2007, p.67.)

The lower heating value (LHV) is obtained when the latent heat of water is excluded from the results. The LHV is usually used when comparing results of different materials. (Rosillo-Calle et al. 2007, p.67.)

The third option is to define **LHV as received**. It is the lowest of all because the energy needed for evaporating the natural moisture, the water of the chemical bounds and the water arising as a result of combustion reactions need to be subtracted from the HHV. (Alakangas 2000, p. 28.) However, LHV as received is not discussed any further in this study.

3.5.1 Measuring the Higher Heating Value

In order to *calculate* the HHV, one of the following equations can be used:

$$\begin{aligned}\mathrm{HHV} = {} & 0.13491 \times \mathrm{X_C} + 1.1783 \times \mathrm{X_H} + 0.1005 \times \mathrm{X_S} \\ & -0.0151 \times \mathrm{X_N} - 0.1034 \times \mathrm{X_O} - 0.0211 \times \mathrm{X_{Ash}}\ [\mathrm{MJ/kg}]\end{aligned} \tag{3.2}$$

where X_i = weight percent of the substance *i* on a dry basis (Rosillo-Calle et al. 2007, p.67)

or

$$\mathrm{HHV} = 338.2 \times \mathrm{C} + 1442.8 \times \left(\frac{\mathrm{H-O}}{8}\right) + 94.2 \times \mathrm{S}\ [\mathrm{kJ/kg}] \tag{3.3}$$

where C, H, O and S are the weight percents of the substance on a dry and ash free basis (daf). (Raiko et al. 2002, p.53) In both equations it can be seen that carbon, hydrogen and sulfur affect the HHV positively and oxygen negatively. The equation 3.2 also shows that nitrogen and ash have a negative effect on the heating value.

To *measure* the higher heating value of bamboo, the ASTM-standard D5865 was applied and a modern bomb calorimeter (model LECO AC500) was used. The bamboo sample had already been oven-dried to a constant weight in a 60-degree oven and its sulphur content had been measured with another device. A 0.6-0.7-gram-sample was

weighted and placed inside the chamber ("the bomb") and the weight together with the measured sulphur content were entered in a computer program as initial values.

Figure 3.2 *Placing the chamber into the water bucket in a modern bomb calorimeter model LECO AC500.*

A cotton thread was adjusted into the chamber so that it touched the bamboo sample. The chamber was carefully closed and placed into a "bucket" (as seen in figure 3.2) which was filled with water (the volume and temperature are known) and two electrodes were connected into the chamber. An electrical current was lead through these electrodes into the cotton thread which then would ignite the bamboo sample. The chamber was filled with pure oxygen and the pressure rose up to 400 psi (about 27 bar) to ensure the complete combustion. The device was closed and the measurement was started by the computer. The advances could be seen on the computer screen and the program automatically calculated the higher heating value of the sample on a dry basis. The calculations are based on the temperature change in the water and related to the amount of the combusted sample.

The complete results can be seen in Appendix 2 and a summary in subsection 3.5.4. All the measurements were done in the Combustible Analysis Laboratories at the Electric Research Institute, Cuernavaca, Mexico.

3.5.2 Lower Heating Value

When the HHV is known, the lower heating value is obtained by the following equation (3.4):

$$\mathrm{LHV} = \mathrm{HHV} - 0.02411 * \mathrm{H}\,\% * \frac{\mathrm{M_{H2O}}}{\mathrm{M_{H2}}} \tag{3.4}$$

where

LHV = lower heating value
HHV = higher heating value
0.02411 = enthalpy difference between gaseous and liquid water at 25 °C at constant volume
H % = the amount of hydrogen in the fuel
M_{H2O}/M_{H2} = 8.936 = the molecular mass ratio between water and hydrogen. (Alakangas 2000, p.29.)

Thus the amount of hydrogen in the fuel must be known in order to define the lower heating value.

3.5.3 Results and Comparison

A summary of average heating values for different bamboo species presented in section 3.1 is showed in table 3.7. More specific values can be found in Appendix 2 at the end of this study.

Table 3.7 *The heating values of different Huatusco bamboo species on a dry basis (IIE 2012a; IIE 2012b).*

Name of bamboo	HHV (MJ/kg)	LHV (MJ/kg)
Bambusa Old Hamii Munro	18.50	17.20
Bambusa Vulgaris Vitata	18.19	16.91
Bambusa Vulgaris Schrader	18.36	17.07
Dendrocalamus Strictus	18.68	17.38
Dendrocalamus Asper	18.59	17.31

Table 3.7 shows, that there are only small differences between different bamboo species but that Dendrocalamus Strictus, Dendrocalamus Asper and Bambusa Old Hamii Munro show the highest LHVs. To be able to understand the magnitude of these values better, reference values for other biomasses and coal are offered in table 3.8 as follows.

Table 3.8 *The lower heating values for different biomasses and coal on a dry basis.*

Biomass	HHV (MJ/kg)	LHV (MJ/kg)
Wood[1]	21.00	19.50
Black Coal[1]	29.60	28.70
Phalaris arundinacea (Reed Canarygrass)[2]	18.49	16.83
Bagasse of Sugar Cane[3]	19.25	17.80

[1]Raiko et al. 2002, p.137; [2]Alakangas 2000, p. 106; [3]Agüero et al., p.2.

As seen in subsection 3.5.1 in equation (3.2) carbon, hydrogen and sulfur content have a positive effect on the heating value of the fuel whereas nitrogen, oxygen and ash lower

the value. For example wood has more carbon and less ash than bamboo and hence the heating value is higher as seen in tables 3.6, 3.7 and 3.8. All biomasses also include a high amount of oxygen. Coal then again has very little oxygen and a lot more carbon than biomasses. Therefore it has a high energy content (despite its high ash content).

3.6 Size Distribution and Bulk Density

The size of the feedstock is an important factor in gasifiers. Very fine or fluffy fuels may cause flow problems in the bunker section which lead to pressure drop. The pressure drop then again leads to smaller gas loads which cause lower temperatures and result in tar production. On the other hand really big feedstock particles lower the reactivity of the fuel causing start-up problems and poor gas quality. In general acceptable fuel sizes range from 8 x 4 x 4 cm to 1 x 0.5 x 0.5 cm. (FAO 1986, p. 31.) This is a reference for wood chips but since bamboo is similar to wood in many senses the same sizes can be considered.

Bulk density means the weight of all the fuel particles divided by the volume they occupy (kg/m^3) as seen in equation (3.5):

$$\rho_{bulk} = \frac{\text{Total mass of biomass particles}}{\text{Bulk volume occupied by biomass particles}} \quad (3.5)$$

The fuels with high bulk density are advantageous because more energy is obtained with one charge of the gasifier. Low bulk density fuels sometimes have troubles to flow under gravity causing low syngas heating values. (FAO 1986, p. 31.) Bulk density can be increased by pelletizing or briquetting the fuel.

Ganesh (2003) gives two bulk density values for different pieces of bamboo as seen in table 3.9 below.

Table 3.9 *Bulk densities of bamboo. (Ganesh 2003, p.5)*

Bamboo	Bulk Density
Cut to1-2 inch pieces	300 kg/m^3
Dust (250 microns)	140 kg/m^3

The bamboo chips used for gasification in Huatusco, Veracruz are approximately the size of 1-2 inches (2.5-5 cm) so the bulk density is approximately 300 kg/ m^3.

3.7 The Pre-processing of Bamboo

The idea of fuel pre-treatment is to produce an upgraded fuel from the harvested biomass. It aims at homogeneous size and quality, increased energy density and reduction of impurities such as stones, earth or sand etc. (Van Loo & Koppejan 2008, p. 64) Ac-

cording to the investigation of Bambuver A.C. (2013b), the best time to harvest bamboo, which is used for energy production purposes, is when it has reached the age of two to three years. By then it has achieved its maximum amount of biomass. (Bambuver 2013b, p.19)

After harvesting, the bamboo needs to be dried in order to reduce humidity, to decrease weight and thus save in transportation costs (if transportation is needed), to improve the mechanical characteristics and to protect the bamboo from external organisms. The energy content of the fuel depends on moisture content and thus the efficiency of the process also depends on that. The time needed for drying varies by the amount of humidity, the thickness of the stem walls, bamboo's maturity grade and the drying conditions of course. If the stems are dried in an open air storage, it takes up to 45-90 days to dry. Then again if stoves or solar heaters are used, the drying time can be reduced to 4-7 days. (Bambuver 2013b, p.26.) Then naturally the costs are higher because the drying devices consume energy. It should be kept in mind that downdraft gasifiers require very dry feedstock with maximum of 20 % of humidity.

When the bamboo is dry enough it has to be cut to splinters and chips of suitable size (see section 3.6). A wood chipper, as seen on the left in figure 3.3, can be used for this purpose. The bamboo chips cut by the chipper can be seen on the right. The feedstock is usually fed into the gasifier through different conveyors. A homogeneous fuel size is an advantage also when using automated systems.

Figure 3.3 *A chipper in operation and the produced bamboo chips in Huatusco Veracruz.*

The storage area should be located near the energy production unit in order to minimize the costs and environmental effects caused by logistics. An uninterrupted supply of feedstock has to be arranged. (Kerlero de Rosbo & de Bussy 2012, p.50.) If there is a time gap between production and utilization, a long-term storage needs to be provided. Normally biomass is stored in piles but special attention has to be paid in that. Biological and biochemical degradation as well as chemical oxidation may sometimes occur in the piles. These result in heat development which might cause self-ignition. Also dry-matter losses, changes in moisture content, and health risks (growth of fungi and bacteria) should be taken into account. (Van Loo & Koppejan 2008, p.84) Besides the bio-

mass storage, other process utilities such as potential auxiliary fuels, lubricating oils, gas cleaning products et cetera need to be preserved nearby. All these are important factors to ensure a stable and safe operation of the plant. (Kerlero de Rosbo & de Bussy 2012, p.50.)

4. THE HUATUSCO PROJECT

The gasification system discussed in this thesis is being built in Huatusco, Veracruz. Section 4.1 offers an overview of the whole project and its diverse benefits. The gasifier will be installed at a hotel so a preliminary investigation on its electricity consumption was carried out to see how the production of the gasifier would affect the hotel. This is discussed in subsection 4.2.2. At the end of chapter 4 the gasification plant is briefly presented.

4.1 Overview

Huatusco is a one of the many municipalities of the state of Veracruz in Mexico with the population of approximately 55,000. The state is located on the coast of the Gulf of Mexico but it spreads about 200 km towards the inlands of the country. Huatusco is situated in the mountainous zone of Veracruz about 115 km from the coast. The average altitude of the municipality is 1344 meters above the sea level but there are lower valleys and higher peaks as well. The Huatusco area is abundant of water: there are many small rivers and the annual rainfall is approximately 1825.5 mm (cf. the annual precipitation in Finland being 600-700 mm (Finnish Meteorological Institute)). The soil in Huatusco is a mix of cambisol and wet soil which makes it very sensitive for erosion. The original name of the town was Otla-quiquiztlan which is indigenous language Nahuatl and curiously means ”The place of bamboo trumpets”. (The Government of Huatusco 2014.)

Because of the high altitude the air pressure is lower than the standard value and because of the rain the air is usually very humid. The average temperature varies between 9 and 23 degrees centigrade but obviously the absolute values sink lower or rise higher. (The Government of Huatusco 2014.) These factors need to be considered in the measurements, calculations and simulations because they affect the quality of the synthesis gas.

Bambuver A.C. is a non-profit organization that cultivates bamboo in Huatusco. They have 200 hectares of plantations and they use bamboo for making furniture and construction material in their workshop. In cooperation with the Electrical Research Institute bamboo is also investigated as a fuel for a downdraft gasifier. (IIE 2014a) An experimental gasifier has already been built and it is located at the workshop of Bambuver (see figure 4.1 for location). The family that owns Bambuver also has other business activities in the area of Huatusco. (Garcia & Olvera 2013) One of them is a hotel resort called Hotel Los Cocuyos and the pilot gasification plant is going to be in-

stalled at the grounds of the hotel. It is located practically across the street of the workshop.

Figure 4.1 *The location of the experimental gasifier and the hotel.(Google Earth)*

4.2 Benefits of the Project

The gasification project discussed in this thesis has a positive influence on the municipality of Huatusco Veracruz. It will produce technological, economical, environmental and social benefits for Bambuver A.C. and for the whole area of Huatusco.

The design and dimensioning of the gasifier is done by the Electrical Research Institute but Bambuver is responsible for the construction of it. Hence they are obtaining technological advantages by developing their own know-how about gasifiers that can later be applied for other similar projects. This would also benefit them economically if they want to start manufacturing gasifiers. In remote communities, where no electrical grid exists, the economical benefits can be achieved by producing low-cost electricity via gasification instead of using diesel as a combustible. This is also an environmental aspect when fossil fuels can be replaced by renewable feedstock. Hence less greenhouse gases will be released in the atmosphere (see the next subsection). Another environmental benefit is that bamboo can be used to recover idle or degraded soil and to prevent erosion. This is of great interest in areas like Huatusco where the soil is already very delicate.

The social benefits include for example bringing electricity to the areas where it does not already exist (2.2 % of the Mexican population (INEGI 2014)), improving

electricity quality in rural areas, being independent on price changes of fossil fuels and generating employment in bamboo plantations and in gasifier manufacture. Employment creation is especially crucial for rural areas where unemployment forms a bigger problem than it does in the cities. Gasification and biomass cultivation could give possibilities for local economy to develop when the fuel expenditures remain within the region, young people to find job opportunities in their own villages and thus slow down the migration to towns.

4.2.1 Avoided CO_2 Emissions

Bamboo has many great characteristics as a construction material as explained in chapter 3 but moreover it prevents erosion, increments water reserves and regulates the oxygen and carbon dioxide balance of the atmosphere.

In the study carried out by Romero Tehuitzil et al. (2014) it is estimated that bamboo is able to capture 47.64 t/ha/year of CO_2. Considering a 50 kW gasifier and a capacity factor of 33 %, 144,540 kWh of electricity would be generated in a year. Using the methodology of the United Nation Framework Convention on Climate Change (UNFCCC) for small scale projects, an emission factor of 0.5722 kg/kWh was obtained. This value is a calculated average for most common fossil fuels used in Mexico. The avoided amount of CO_2 would hence be 82.7 tonnes a year. Although biomass gasification is considered carbon neutral, it is estimated that the processes also generate some CO_2 emissions mainly because of transportation. When the generated quantity is subtracted from 82.7 t/yr, a final value of avoided CO_2 emissions would be **82.4 t/year**. Thus in an environmental point of view the Huatusco gasification project is seen as a viable option for reducing greenhouse gases. (Romero Tehuitzil et al. 2014.) The effect of carbon credits is not considered in the study but they might raise further interest in biomass gasification projects in the future.

4.2.2 The Effects on the Hotel

As mentioned earlier, the gasification system will be installed at Hotel Los Cocuyos in Huatusco. The local and renewable feedstock ensures the sustainability of the gasification project and helps the hotel to be energetically self-sufficient and independent on the distribution brakes of electricity and on the rising prices of fossil fuels. The hotel can also get a green and eco-friendly image which is an advantage in today's tourism industry. The logistic expenses will be at minimum because of the nearby location of the bamboo plantations.

To get more information about the hotel's electricity consumption and to make sure that the produced energy could be utilized there, an electricity meter was installed at the hotel. The measurements started on the 20th of March 2014 at 11.30 and lasted until the 8th of April 2014 at 13.59. Together this forms 19 days, 2 hours and 29 minutes. The data was saved every half an hour and the minimum, average and maximum consumption was recorded. (IIE 2014b.) The period was relatively short so it does not give an

extensive picture of the consumption. That is why some old electricity bills of the hotel were also reviewed to see how the consumption varies over a longer period of time.

The average daily electricity consumption can be seen in figure 4.2. It was calculated from the measured values and it varies between 8 and 14 kW. The demand starts rising at around 7 am when the restaurant opens and people start waking up. During the day it maintains a certain level but rises again in the evening when the sun goes down and lighting is needed. After 10 pm it starts decreasing when the restaurant closes and people are starting to go to sleep.

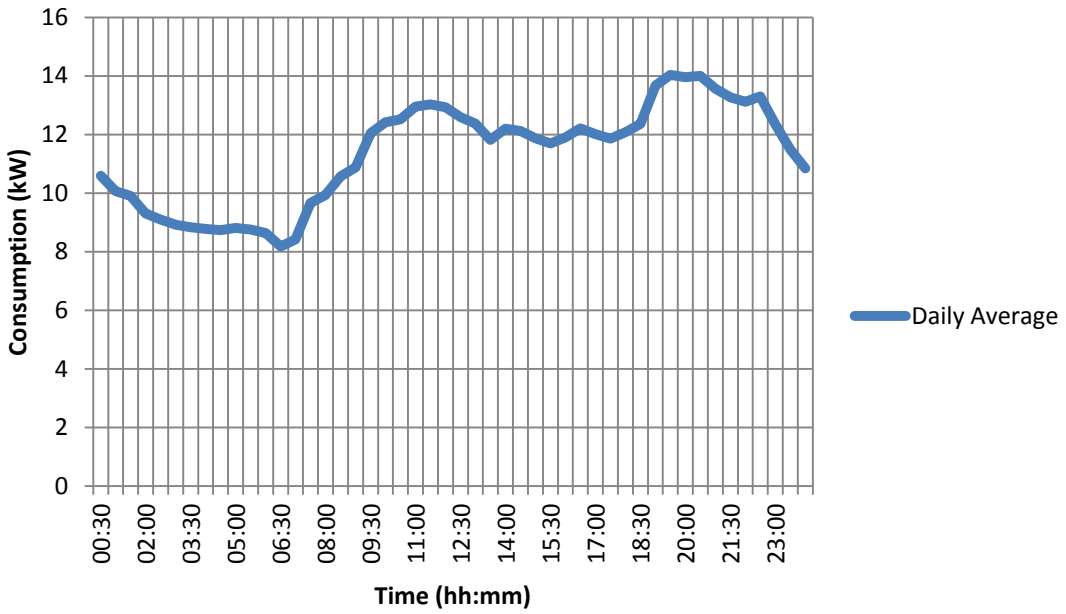

Figure 4.2 *An average daily consumption of the hotel.(IIE 2014b)*

The figure 4.3 illustrates the total consumption of the hotel during the measurement period. The consumption (minimum, average and maximum values) of all three phases is summarized. A few peaks can be seen and the highest of them reaches almost 70 kW. Probably a start-up of a machine or a device such as air-conditioning or a pump caused these peaks. Mostly the demand varies between 8 and 25 kW. It can also be seen that at weekends the consumption is higher because there are more guests and the hotel also organizes activities (for example live music at the restaurant). The weekends are marked with red frames in the figure.

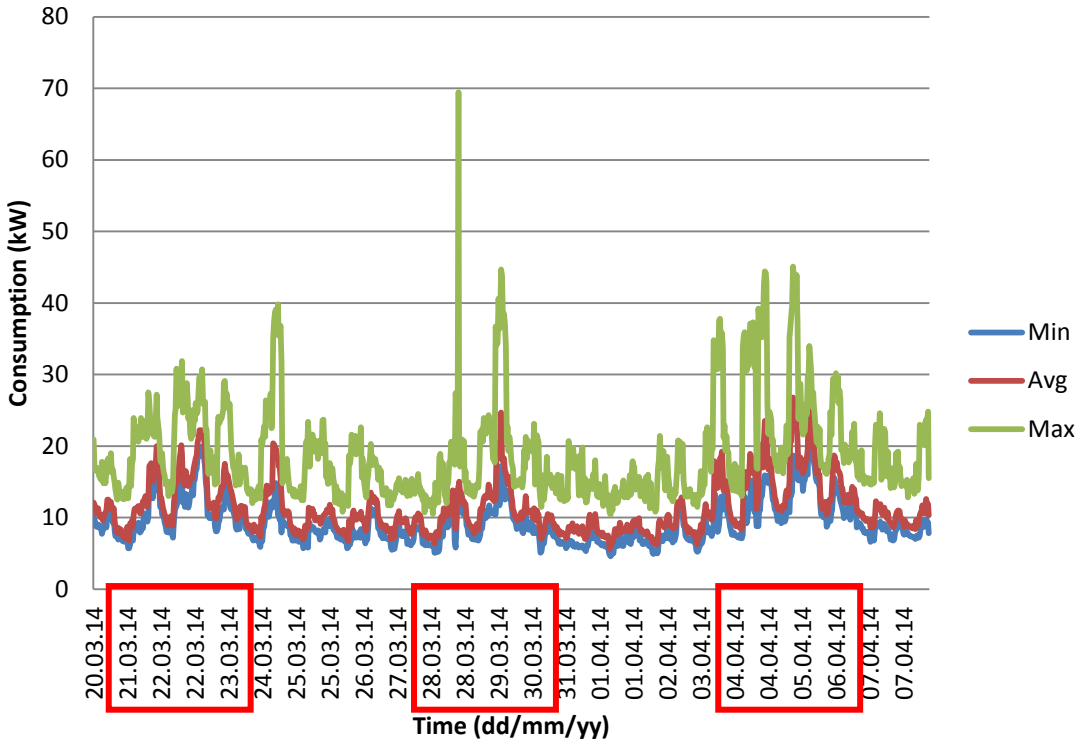

Figure 4.3 *Total consumption (summary of the three phases) of the hotel during 20.3.-8.4.2014. (IIE 2014b)*

The figure 4.4 is drawn by using the information found in the old electricity bills of the hotel. The monthly consumption between December 2011 and October 2013 is presented and it seems to vary approximately from 10 to 17 kW. No huge fluctuations can be seen and the demand seems to be in line with the average daily demand of figure 4.2.

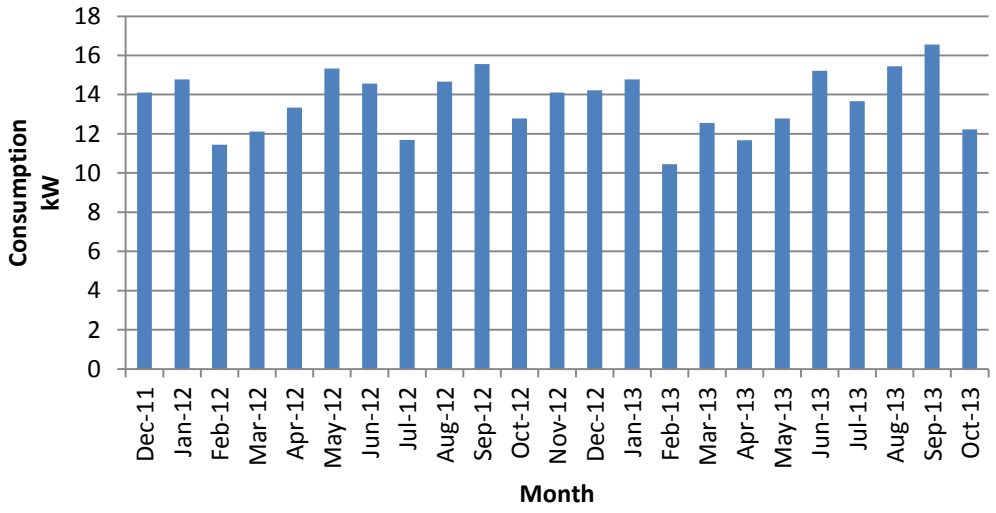

Figure 4.4 *Total consumption of the hotel between December 2011 and October 2013.*

According to these graphs (4.2-4.4) the gasifier would generate more electricity than is needed at the hotel if the produced power reaches 50 kW. A 50 kW engine-generator would also be powerful enough to lower the peaks seen in figure 4.3. If extra electricity

is produced, it can be injected into the grid and at the end of a billing period the federal electricity company of Mexico, CFE (Comisión Federal de Electricidad), will subtract the production from the consumption and the hotel only pays for the difference. This would be beneficial for the hotel as their electricity bill decreases. However, the pre-processing of biomass, mainly the drying, cutting and transportation of bamboo, also requires energy. The total amount of this energy is so far unknown and deeper investigation on this should be done in order to be able to estimate the real benefits for the hotel.

4.3 Plant Description

In general a gasification process consists of four different phases: 1) biomass handling and feeding, 2) gasification, 3) gas cleaning and cooling, and 4) gas conversion into electricity. These phases can be seen in figure 4.5 marked with different colors. The purple color indicates the side streams originating from the gasification process. Also all the inputs and outputs are presented. The flow chart represents the Huatusco gasification system.

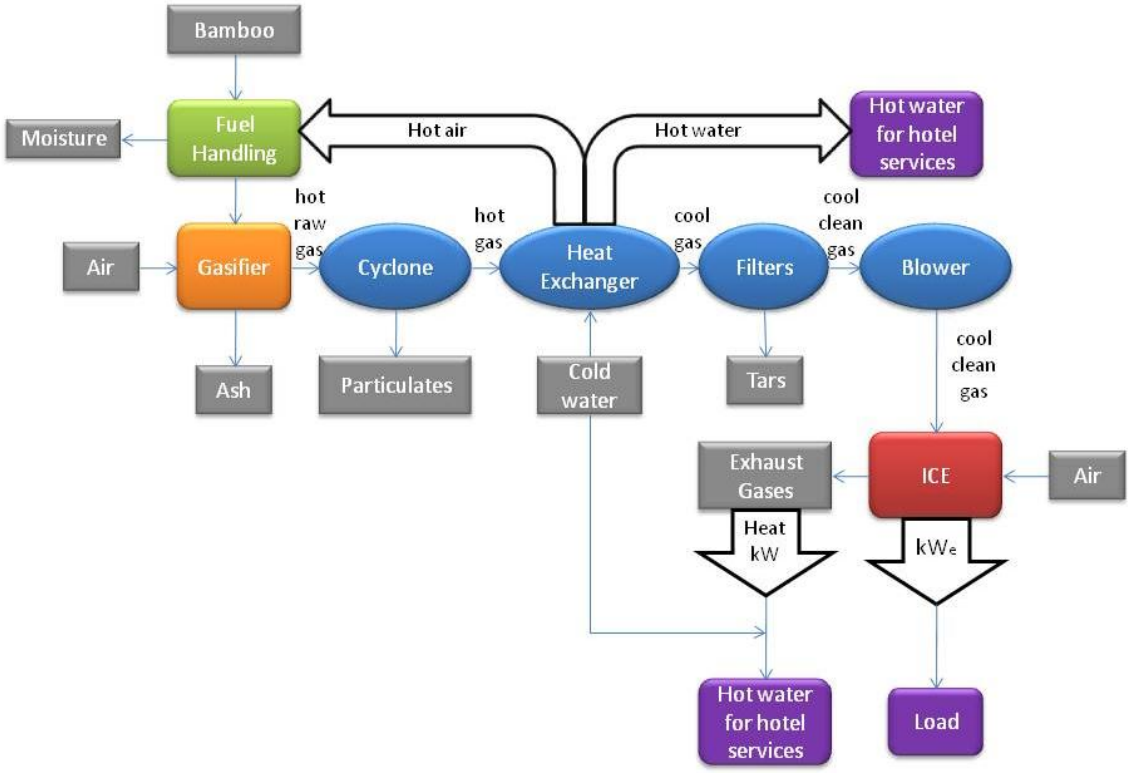

Figure 4.5 *A flow chart presenting the Huatusco gasification plant (own elaboration).*

In the plant pre-dried bamboo chips are fed into the gasifier through an automated conveyor. After the gasification reactions the product gas enters the cyclone where the particulates of the diameter bigger than 5 microns are removed from the gas and captured at the bottom of the cyclone. Then the gas is cooled down and filtered so that it is

suitable to enter the internal combustion engine (ICE). The heat exchanger produces heat that can be utilized for preheating the air that is fed into the gasifier, pre-drying the bamboo or for other heating purposes (e.g. the hotel swimming pool). An internal combustion engine together with a generator is used to convert the synthesis gas into electricity. Also the hot exhaust gases of the engine can be utilized for heating purposes.

During the time range of this study the plant shown in figure 4.5 was still under construction. However, a smaller (~40 % of the real size) experimental gasifier had already been built and several test runs were carried out with it (see chapter 6). The small scale system only consists of the gasifier, a heat exchanger, some filters, a blower and a flare. All the calculations presented in the next chapter are done for the real scale system.

5. ESTABLISHMENT OF PROCESS PARAMETERS FOR THE HUATUSCO PLANT

In this chapter the entire gasification system will be characterized and discussed. The characterization is done step by step. It starts from deciding the size of the engine-generator which is done in section 5.1. After the size has been chosen, the quantity of gas that the engine requires in order to produce the wanted amount of electricity must be calculated. The relation between the quantity of gas and the physical dimensioning of the gasifier is defined in section 5.2. The topic is discussed very briefly because it is not in the scope of this study.

The other process variables are then chosen so that the needed volume flow of the gas is obtained. To study the effect of different operating conditions and to find an optimal range for different variables, a sensitivity analysis using software called Thermoflex is carried out. After that a more detailed simulation is done by using the values obtained by the sensitivity analyses. This is discussed in section 5.4. To be able to understand better the results of Thermoflex, comparative Excel-calculations utilizing atomic balances are elaborated for this study. They will be presented in section 5.5 and in more detail in Appendix 4. An important key ratio for gasification is its overall system efficiency. Section 5.6 explains how it is calculated and lists the results.

5.1 Defining the Size of the Engine-Generator

The size of the gasifier and the engine-generator was defined according to a few different factors. To be able to maintain the expenses on a bearable level for each party involved, a 50 kW gasifier was chosen. A smaller gasifier would not have been very rational and a lot bigger one would have increased the costs significantly. Also as being a prototype, a small scale application is a safer option. Bambuver A.C. has a limited amount of bamboo plantations so it also had to be ensured that there will be enough raw material available for gasification. This is briefly discussed next, in subsection 5.1.1. After that, subsection 5.1.2 lists the specifications of the engine-generator chosen for the project.

5.1.1 Availability of Bamboo

According to the investigation of Castañeda (2004) bamboo is able to accumulate biomass an average amount of 25.92 t/ha in a year. (Castañeda 2004, p.25) Considering the

40 hectares of area of cultivation, there would be 1036.80 t/year of accumulated biomass available. This equals to **118.36 kg/h.**

As will be seen later in section 5.3, the consumption of bamboo for a 50 kW gasifier is **62.9 kg/h**. Thus it can be stated that there will be plenty of bamboo available for the project. It is also assured that the bamboo plantations won't be over exploited and the energy production will be sustainable. This will even leave space for building another small scale gasifier or later replacing the 50 kW gasifier with a bigger one.

5.1.2 The Engine-Generator Specifications

When the size of the engine-generator is decided, the next step is to calculate how much synthesis gas it needs so that it can produce the wanted power. A possibility to cooperate with a company called Cummins came up, and for this project they offered an engine-generator that had been fuelled initially with natural gas but was then modified to run on synthesis gas. It is a pilot model that is going to be tested in the plant of Huatusco.

Natural gas consists practically of methane. In synthesis gas only a small fraction is methane and the dominating burning gases are hydrogen and carbon monoxide. Hydrogen burns quicker than methane or carbon monoxide (flame speed of H_2 2.83 m/s vs. CO 0.52 m/s (Kishore 2010, p.781)) which can cause pre-ignition, knocking and engine backfiring. In order to avoid these problems some changes in the engine need to be done and also the output of engine is reduced down to 50-70 % of the typical natural gas output. (Clarke Energy.) The rated power of the Cummins genset with natural gas is 175 hp (≈130.5 kW) but using synthesis gas it falls approximately to 40-50 kW (depending on the heating value of the synthesis gas). The following calculations are presented using the Cummins genset specifications showed in table 5.1.

Table 5.1 *Cummins Engine-generator GTA 8.3 SLB specifications.*

Engine Specification	Dimension
Rated Power	40-50 kW
Total Displacement	8.3 liters
Cylinders, n	6
RPM	1800
Volumetric Efficiency	0.8
Compression Ratio	10.5:1
Starting Type	Spark Ignited

According to these specifications, the engine swept volume can be defined as follows (Kishore 2010, p. 769):

$$\text{Engine Swept Volume} = V_s = \text{Total Cylinders' Swept Volume} \tag{5.1}$$
$$= \frac{1}{2} * \text{RPM} * \text{Total Displacement} = \frac{1}{2} * 1800 * 8.3\ \text{dm}^3$$
$$= 7.47 \frac{\text{Nm}^3}{\text{min}} = 448.2\ \frac{\text{Nm}^3}{\text{h}}$$

Swept volume is related to the amount of air that the engine can suck in. Normally the engines operate with the air-gas ratio of 1.1:1.0. This means that 1 m^3 of gas needs 1.1 m^3 of air to burn completely in the engine. Thus the air and the gas together form 2.1 m^3. Now the gas intake rate can be calculated as follows (Kishore 2010, p.769; FAO 1986, p.124):

$$V_g = \frac{\text{Volumetric efficiency} * V_s}{2.1} = \frac{0.8 * 448.2 \frac{\text{Nm}^3}{\text{h}}}{2.1} = 170.74 \frac{\text{Nm}^3}{\text{h}} \tag{5.2}$$

This means that about **171 Nm^3/h** of synthesis gas is needed to feed the engine so that it generates a 40-50 kW power. The Cummins engine-generator can be seen in the photos below.

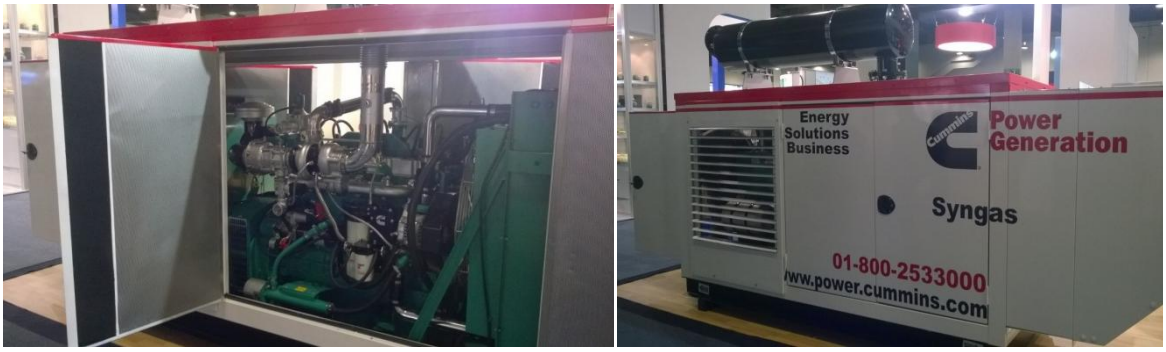

Figure 5.1 *The Cummins genset for synthesis gas (own elaboration).*

5.2 The Physical Dimensioning of the Gasifier

An important link between engine specifications and dimensioning of the gasifier is a concept called *hearth load*. It is introduced for example by Food and Agriculture Organization of the United Nations (FAO 1986) and Basu (2013).

Hearth load (B_g) is defined as the amount of synthesis gas (in STP-conditions) divided by the surface area of the throat of the gasifier [m^3/cm^2*h]. The throat has the smallest circumference in the gasifier and it is also the spot where the air is blown to.

B_g has a maximum value of 0.9. (FAO 1986, p. 36) Using this value and the gas intake rate calculated in the previous section the throat area of the gasifier can be defined as follows:

$$A_{throat} = \frac{V_g}{B_g} = \frac{170.74 \frac{m^3}{h}}{0.9 \frac{m^3}{cm^2 * h}} = 189.71 \text{ cm}^2 \quad (5.3)$$

Using the formula of the area of a circle the diameter of the throat of the gasifier can be calculated as follows:

$$A_{throat} = \pi \frac{{d_{throat}}^2}{4} \rightarrow \mathbf{d_{throat}} = \sqrt{\frac{4 * A_{throat}}{\pi}} = 15.54 \text{ cm} \quad (5.4)$$

This is the first physical dimension when starting to design the gasifier itself. It is worth mentioning that the downdraft gasifier that is actually being built in Huatusco has a throat diameter of 15 cm. Literature provides useful instructions for dimensioning the rest of the gasifier (FAO 1986; Basu 2013) but the topic is not discussed any further in the scope of this thesis.

5.3 Sensitivity Analysis on Thermoflex

When the genset size had been decided, the other process variables needed to be established so that enough good quality gas could be generated. The gasification process is very sensitive: small changes in the amount of air, feedstock quality or temperature affect the syngas quality and thus also its heating value which has an effect on the engine-generator and on the system efficiency. That is why it is important to find an acceptable range for the gasifier to operate and hence a sensitivity analysis using an engineering software program called Thermoflex was carried out. The next subsections explain how the simulations were done and the results are listed in chapter 7.

5.3.1 Background of the Simulations

Thermoflex is a rather simple and convenient program for studying the influence of fuel and process parameters and predicting the behavior of the entire gasification system. It utilizes thermodynamic equilibrium models (heat balances) to carry out the simulations and the system is built by the components that exist in the program's library. (Thermoflow 2014).

As seen in the process diagram presented in Appendix 3 the simulated system includes a gasifier, gas conditioning equipment (incl. a wet scrubber), a heat exchanger, and an ICE and every device is at the atmospheric pressure. However, it differs somewhat from the real system (see figure 4.5 in chapter 4). In the simulations water is injected into the gasifier but this step is left out in Huatusco. Also the wet scrubber is left out because of the difficulty to handle the residue waters on the site. Other gas conditioning equipment (such as cyclone and filters) that will be used in the real system is not included in the simulation. This is because Thermoflex is mainly used to model large, industrial installations so e.g. small scale cyclones are not available in the program li-

brary. The program also obliges the user to include the whole gas conditioning system in the simulation. Choosing single components is not possible. Injecting water into the gasifier is a mandatory step too; otherwise the program does not run.

Four different variables were modified one by one to carry out the sensitivity analyses. They are the **gasification temperature**, the **air-fuel ratio** (the ER), the **moisture content** of the fuel and the **temperature of pre-heated air**. Because the gasification system includes many different components, changing the operation conditions of the gasifier affects the performance of the entire system. Especially the engine-generator gets affected by the changes and at certain moment a point is reached when the ICE would not run anymore without changing its parameters. Hence the simulations are carried out as far as the software allows them to run without making changes to the ICE.

The variables used in the simulations of the **gasifier temperature** are:

- Ambient temperature = T_{amb} = 15 °C
- Ambient pressure = p_{amb} = 881 mbar
- Relative humidity = Ψ = 60 %
- Moisture content of the fuel = MC_{fuel} = 15 %
- Gasifier temperature = $T_{gasifier}$ = 500…1000 °C
- Air-Fuel-ratio = A/F = varies when temperature is changed

The first study was carried out by varying temperature inside the gasifier for the range 500-1000 °C. Higher temperatures would have required changes for the ICE conditions. The ambient conditions were partly measured on the site and partly checked in a weather forecast. The temperature of the gasifier and the air-fuel ratio are each other's functions in Thermoflex meaning that if temperature is fixed by the user, the software adjusts the A/F-ratio according to the temperature. Then again if A/F-ratio is fixed, the temperature will vary. Both variables cannot be fixed at the same time.

When simulating the effect of the **air-fuel-ratio**, the following variables were used:

- T_{amb} = 15 °C
- P_{amb} = 881 mbar
- Ψ = 60 %
- MC_{fuel} = 15 %
- $T_{gasifier}$ = varies when A/F is changed
- A/F = 0.5…2.0

Table 5.2 shows the corresponding values of the equivalence ratio (ER) obtained by the equation (2.9). The ER is already discussed in subsection 2.6.2 and thus it is easier to understand and compare than the A/F-ratio. The stoichiometric A/F means the air/fuel relation when the bamboo is completely combusted. The calculations for this can be seen in Appendix 4 (the value 4.64 is a result obtained in Huatusco's conditions).

Table 5.2 *The air-fuel-ratios and the calculated ER (own elaboration).*

A/F (simulated)	A/F (stoichiometric)	ER
0.50	4.64	0.11
0.75	4.64	0.16
1.00	4.64	0.22
1.25	4.64	0.27
1.50	4.64	0.32
1.75	4.64	0.38
2.00	4.64	0.43

The variables used in the third simulations for the **moisture content of the fuel** are:

- T_{amb} = 15 °C
- P_{amb} = 881 mbar
- Ψ = 60 %
- MC_{fuel} = 0…25 %
- $T_{gasifier}$ = 800 °C
- A/F = 1.76

Finally the last simulations for **the temperature of the pre-heated air** were carried out using the following variables:

- T_{amb} = 15 °C
- P_{amb} = 881 mbar
- Ψ = 60 %
- MC_{fuel} = 15 %
- $T_{gasifier}$ = varies when the air is heated
- A/F = 1.76
- T_{air} = 50…600 °C

The last simulation is done with a slightly different system. A heat exchanger is added into the system to utilize the hot exhaust gases of the ICE in order to pre-heat the air that is fed into the gasifier (see figure 5.2 for the system but note that the variables are different than in the sensitivity analysis). Normally the air is at ambient temperature but now it is heated from 50 up to 600 °C. The A/F-ratio is fixed at 1.76 and the temperature of the gasifier is adjusted by the software.

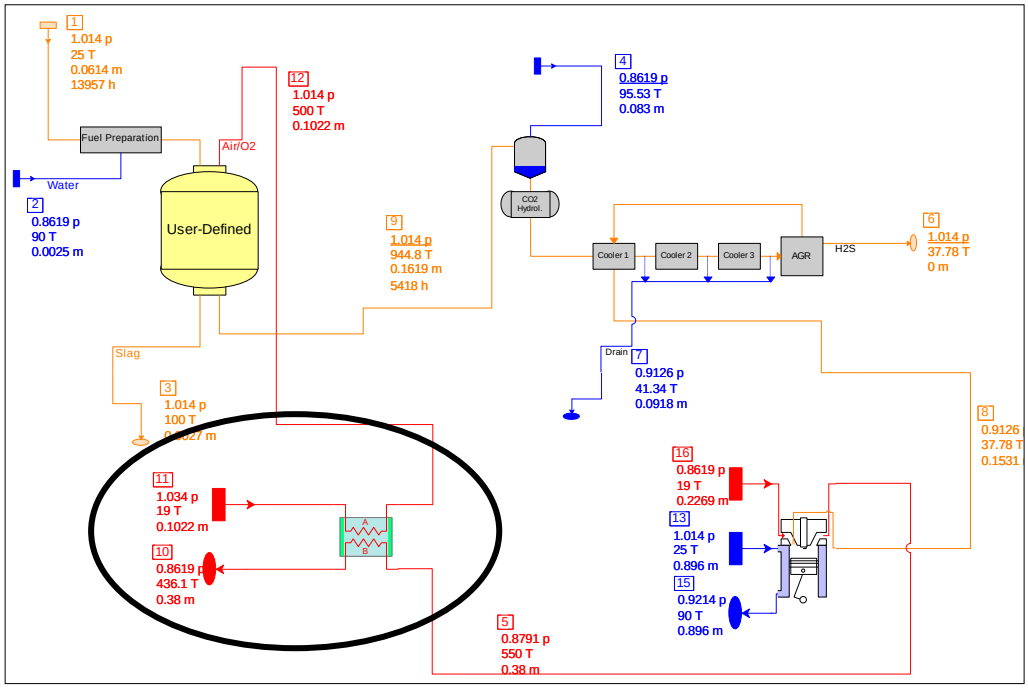

Figure 5.2 *The gasification system whit a heat exchanger (IIE 2014a).*

All the results of the sensitivity analyses presented in this section are listed in chapter 7.

5.4 A More Detailed Thermoflex Simulation

The idea of the more detailed simulation is to examine the process values (e.g. the mass flows) in more detail. According to the sensitivity analyses discussed in section 5.3, the following values were chosen for the simulation:

- T_{amb} = 15 °C
- P_{amb} = 881 mbar
- Ψ = 60 %
- MC_{fuel} = 15 %
- $T_{gasifier}$ = modified by the software
- A/F = 1.7 and thus ER = 0.37

The A/F-ratio was fixed and the gasifier temperature was modified by the software.

A process flow chart of the whole system can be found in Appendix 3 but it should be noticed that the mass flows in the figure are slightly different than in this example. The system, however, is similar. In the same Appendix also a flow schematic of the gasifier unit, the heat balance results and the fuel properties are presented.

Table 5.3 below shows a summary of inputs and outputs of the downdraft gasifier in the Thermoflex simulation. The ingoing water stream is not shown in the table which explains the difference in mass balances.

Table 5.3 *Inputs and outputs of the gasifier (IIE 2014a).*

	Stream	p (bar)	T (°C)	Mass flow (kg/h)
In	Bamboo	0.881	15	62.9
	Air	1.014	15	109.1
Out	Gas	1.014	858.3	171.7
	Slag	0.881	100	2.8

In Huatusco, Veracruz the ambient pressure is a little below the standard pressure (881 mbar vs. 1014 mbar). This is due to higher altitude. Thermoflex configures automatically some of the operational parameters and for example the air pressure of the gasifier was set to 1014 mbar. The pressure of the fuel inlet and the pressure of the out coming ashes of the gasifier were established to be at the atmospheric pressure of the site (881 mbar). If all the pressures were tried to set to 881 mbar, the simulations did not run.

As explained earlier in subsection 2.6.2, the equivalence ratio (ER) is an important factor in gasification but it is not readily defined by Thermoflex. When the size of the ICE is fixed at 50 kW and the A/F-ratio at 1.7, the software automatically calculates suitable air and mass flows as seen in table 5.3. The A/F-ratio can be defined based on them as follows:

$$\left(\frac{\mathrm{A}}{\mathrm{F}}\right)_{\mathrm{Actual}} = \frac{109.1\,\frac{\mathrm{kg}}{\mathrm{h}}}{62.9\,\frac{\mathrm{kg}}{\mathrm{h}}} = 1.734 \tag{5.5}$$

The stoichiometric A/F-ratio for bamboo is obtained by the calculations shown in Appendix 4 and its value is 4.642 (in Huatusco's conditions). Using the equation (2.9) presented in subsection 2.6.2, the ER can be defined as follows:

$$\mathrm{ER} = \frac{1.734}{4.642} = \mathbf{0.374} \tag{5.6}$$

Thus the chosen mass flows form an acceptable value of the ER.

The mass flow of the produced gas is 171.7 kg/h as seen in table 5.3. When the molecular weight of the gas is assumed to be 23.74 g/mol and the calculations are done in standard conditions, 171.7 kg/h equals to **162 $\mathbf{Nm^3/h}$**. In Huatusco's conditions (881 mbar, 288.15 K) it equals to 197 m^3/h. In subsection 5.1.2 the amount of gas needed by the engine was found out to be **171 $\mathbf{Nm^3/h}$**. Hence it seems that the production is a little bit low but still in the right range. The other results obtained by this simulation are listed in chapter 7.

5.5 Comparative Engineering Calculations

As any complex software, Thermoflex gives straight results without showing or explaining any calculations behind them. The basic engineering calculations (elaborated using Excel), are done in order to understand better the behavior and relations of different factors. They also serve as a background and comparison for the Thermoflex results. If no adequate software is available, a preliminary design of the gasification process can be done by following the Excel calculations presented step by step in Appendix 4. The next subsections 5.5.1 and 5.5.2 briefly present the initial values used in the calculations. The results are shown in chapter 7.

5.5.1 Ambient Conditions

The Excel calculations done for this thesis do not take into account the temperatures or the pressures inside the gasifier system. Only the ambient pressure and temperature of Huatusco are considered. The gasifier system is at atmospheric pressure but its value is different due to the high altitude of the site as seen in the following table. Temperature is assumed to be an average 15 degrees and the relative humidity (Ψ) 60 %.

Table 5.4 *Standard and real conditions of temperature and pressure (own elaboration).*

	STP	**Huatusco (1235 m of altitude)[1]**
T	0 °C	15 °C
p	1013.25 mbar	881 mbar
Ψ	60 %	60 %

[1]Google Earth, coordinates 19.151288, -96.955723

The calculations showed in Appendix 4 are done in standard air temperature and pressure (=STP). Huatusco's results are obtained by the same calculations changing the temperatures and pressures according to table 5.6.

5.5.2 Initial Values

As seen in earlier in subsection 5.1.2 the gasifier needs to produce about 171 Nm^3/h of gas to satisfy the engine-generator's needs. The Thermoflex simulation presented in section 5.3 gives values for the moisture content, the mass flow of bamboo and the ER to reach the wanted amount of gas.

Table 5.5 *The initial values used for Excel calculations.*

Humidity of bamboo	15 %
Mass flow of bamboo = F	62.9 kg/h
ER	0.374

The same values will be used in Excel to be able to compare the obtained results with the results of Thermoflex. The values are repeated in table 5.7 above. Also the composition of bamboo is the same in Thermoflex and in Excel calculations. The results of these calculations are found in chapter 7.

5.6 Definition of the Overall System Efficiency

The overall system efficiency tells how much of the energy stored in a fuel can be converted into an energy output of the system (=electricity). It is defined as the product of the gasifier efficiency (cold gas efficiency), the engine efficiency and the generator efficiency.

Cold gas efficiency is the ratio between the chemical energy in the synthesis gas and the chemical energy of the fuel at room temperature. This is used as a measure of efficiency because the synthesis gas needs to be cooled down to feed it into the ICE and thus the sensible heat will be lost. It can be calculated as follows:

$$\eta_{\text{cold gas}} = \frac{\text{LHV}_{\text{gas}} * \text{Gas flow}}{\text{LHV}_{\text{bamboo}} * \text{Mass flow}} = \frac{4284.11\,\frac{\text{kJ}}{\text{Nm}^3} * 159.44\,\frac{\text{Nm}^3}{\text{h}}}{16{,}334.336\,\frac{\text{kJ}}{\text{kg}} * 62.9\,\frac{\text{kg}}{\text{h}}} \approx 66.50\ \% \qquad (5.7)$$

The values used in equation (5.7) are obtained in the Excel calculations in STP-conditions (see Appendix 4).

The engine efficiency for the Cummins engine using syngas has not been defined yet because it is only a little tested pilot model. That is why the efficiency is estimated according to the literature. Reed & Das (1988, p.114) state that the spark engine operating on synthesis gas can achieve a maximum thermal efficiency of 15-25 %. Graig & Sharma (2013, p.4) have used the value 26.5 % in their calculations, according to FAO (1986, p.124) the efficiency can be estimated as 28 % and the company Pyromex uses values of 28 % and 32 % in their example calculations. Hence an average value of **28 %** will be used in this thesis.

The generator efficiency of the Cummins synthesis gas genset is estimated to be 85-86 %. (Chacón 2014) Now the overall efficiency can be calculated as follows:

$$\boldsymbol{\eta_{overall}}$$

$$= \eta_{cold\ gas} * \eta_{engine} * \eta_{generator} = 0.6639 * 0.28 * 0.86 = 0.1599 \qquad (5.8)$$

$$\approx \mathbf{16.00}\ \%$$

6. EXPERIMENTAL GAS SAMPLING

In order to analyze the gasifier operation or to calculate the energy content of the gas, the chemical composition of the syngas must be known. There are several ways to sample gas and they are explained in section 6.1. The set-up and the experimental procedures carried out with the experimental gasifier are described in the following sections 6.2 and 6.3. After that a detailed step-by-step protocol for gas sampling in-situ is presented.

6.1 Principles of Gas Testing

There are several ways to predict the theoretical composition of the synthesis gas as also seen in this study (balance calculations, computer simulations) but the most relevant results will be obtained by experimental measurements. Gas samples can also be taken to measure the water content of the gas, the amount of tars, quantity and size of particulates but these methods will not be discussed here. (Reed & Das 1988, p. 51.)

The gas composition measurements can be done continuously or periodically. In periodical sampling (also called batch-sampling) the gas sample must be drawn from the system, captured in a suitable container and brought to a laboratory in order to find out the chemical composition. The gas leaks (in or out of the container) easily spoil the sample so extra attention has to be paid. If oxygen is found in the sample, the composition can be converted to an air-free basis by subtracting the oxygen and the corresponding amount of nitrogen from the sample. (Reed & Das 1988, p. 61.)

Continuous sampling (also called on-line sampling) is useful when instantaneous changes in the gas composition want to be observed. There are several methods for on-line analysis: flame observation, combustion calorimetry, infrared absorption, thermal conductivity and mass spectrometry. With infrared absorption the amount of CO, CO_2 and CH_4 can be read continuously. Thermal conductivity detector is used for H_2 determination. Another method to give immediate on-line digital readout of all the gases uses mass spectrometer. Then again a calorimeter is used for defining the higher heating value of the syngas. Also simply observing the gas flame during the operation can reveal many things about the gasifier operation. For example the flame length tends to increase with the gas heating value and the flame luminance increases with hydrocarbon and tar content. (Reed & Das 1988, p.64.) However, the gasifier examined in this chapter is so far an experimental device so no investments in continuous sampling equipment are being made and only batch-sampling methods are used.

6.2 The Set-up

The downdraft gasifier used for carrying out the gas sampling is a small scale experimental device. Its height is 56 cm and diameter 33 cm. The throat diameter is 8 cm and the height 22 cm. Originally, this gasifier was meant to be just a miniature of the real device. That is why it is made of cheaper material called black iron. Black iron is softer than steel and easily exposed to corrosion which makes it a bad material for gasification purposes. Nevertheless, it was considered useful to do test runs with this experimental gasifier despite the possible material problems in order to gain important knowledge of the operation before testing the real pilot plant.

The first test runs were done with the system shown in figure 6.1. The gasifier is connected to a heat exchanger (=HE) where the synthesis gas is cooled down with water that is taken from the nearby river. The cool gas that comes out of the heat exchanger flows through a blower (brand: Leister) before it is burned in a flare (not shown in figure 6.1). The blower works as a suction pump which means that it is dragging the air into the gasifier and forcing the produced gas to flow through the whole system. The first three gas samples were taken using the system presented in figure 6.1. The first one was taken at the red point after the heat exchanger and samples number 2 and 3 after the Leister-blower at the gas outlet.

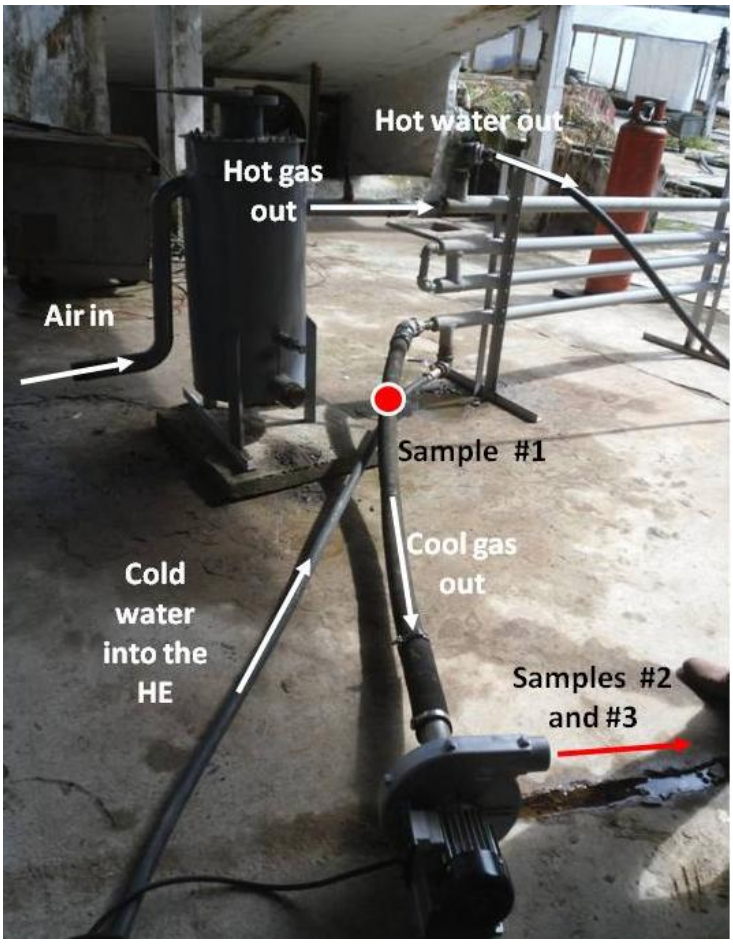

Figure 6.1 *The experimental gasification system using only one blower.*

In order to take a 4th sample, the connections were slightly changed. The Leister-blower was connected to the air inlet of the gasifier to blow air into the throat of the gasifier. Another blower (brand: Becker) was connected after the heat exchanger to work as a suction pump. The sample was taken after the Becker-pump at the gas outlet.

Figure 6.2 *The experimental gasification system at the workshop of Bambuver in Huatusco.*

The procedure described in the next section was done by the system shown in figure 6.2.

6.3 The Experimental Procedure

Before filling in the gasifier, the Becker-suction pump was turned on and the whole system was ventilated well. To begin the experiments the gasifier was ignited using cardboard and carbon. In 10 minutes all the carbon had ignited so 1 kg of bamboo chips was added through the lid. The bamboo applied was Bambusa Vulgaris Vitata cut to 2-3 cm pieces. The Leister-blower was turned on (f=20 Hz) 20 minutes after the ignition. Soon after that the temperature of the gasifier rose significantly as did the temperature of the water coming out of the heat exchanger. Also the pressure inside the gasifier grew and it started to release vapor through the lid. At this point the Leister-blower was turned off because it had probably fed too much air into the system and caused very rapid combustion inside the gasifier. The temperatures of the gasifier, gas or water could not be measured because of lacking equipment.

Fifty minutes after the ignition 2 kg of bamboo was added into the reactor. The gas production seemed stable at this point. Suddenly after 85 minutes of operation no gas

was coming out. The gasifier had shut down because all the 3 kg of bamboo had already been consumed. The rate of consumption was higher than anticipated beforehand. Half a kilo of bamboo was added and the gasifier was reignited. It took almost 1 hour to ignite well and to keep it in operation without the help of the user. Finally, using extra air of the Leister-blower, the temperature rose again and the gas production seemed stable. Four kilograms of bamboo had been placed inside at this point (7 kg in total). 165 min after the first ignition, the gas sampling was finally carried out. The experiment lasted 3 hours in total.

In the next section the sample taking is explained in more detail.

6.4 Protocol for Taking a Gas Sample In-situ

The equipment needed for gas testing can be seen in figure 6.3 and a detailed protocol for carrying out the sampling process is presented afterwards. The idea is to collect a gas sample in-situ and bring it to the laboratory for determining the gas composition by using gas chromatography.

The gas collector is a small cylinder usually made of plastic, glass or metal. One or both endings have stopcocks to prevent the gas sample to escape once it is taken and to enable a safe transportation to a laboratory. A filter holder and glass fiber filters should be used to remove impurities and ensure a good syngas quality. A ball valve is needed to close off the gas stream in the sample probe when the sampling has been finished.

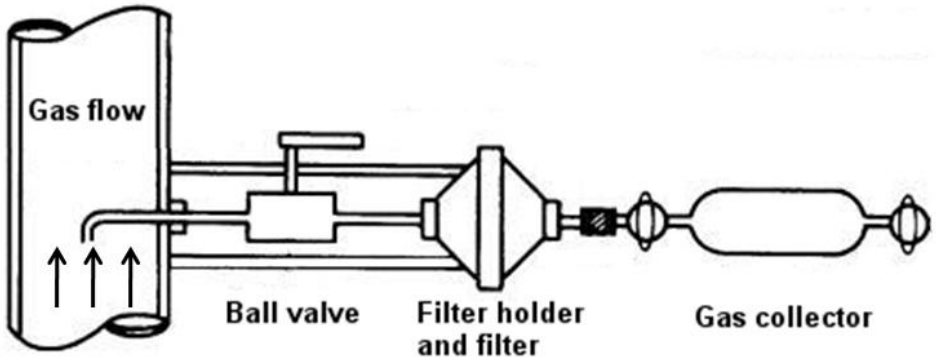

Figure 6.3 *Gas sampling equipment (adapted from Reed & Das 1988, p.60)*

Protocol for gas sampling:

1. Acquire the equipment needed for sampling
    a. Sample probe (tubes and hoses), ball valve, filter holder, filters, gas collector (gas sampling bottles), enough suitable connectors for different parts, sodium hydroxide (NaOH), goggles, gloves, toolbox including a drill
2. Prepare the gas sampling bottles:

   a. Fill ¼ of the collector with NaOH and create a moderate vacuum inside of it (these should be done before going to the site) or
   b. create a vacuum of 25 psi (≈1.7 bar) but do not use NaOH
3. Clean and test all the testing appliances
4. Choose an adequate spot for sampling. The best placement for the probe is where the gas flow is average for the tube
5. Drill a hole into the gas pipe and assemble all equipment. Make sure that through the drilled whole air is dragged out, not leaked into the system
6. When the gasifier is running at steady state (about 30 minutes from the ignition), start sampling
7. Turn the bottle upside down, open the ball valve and the stopcock of the bottle, and let the syngas flow into the gas collector
8. NaOH starts reacting with the syngas and bubbles are formed. When no more bubbles are seen, the collector is full of gas and the sampling can be stopped
9. If sampling bottles without NaOH are used, the time needed for sampling is approximately 5 seconds
10. Close the ball valve carefully so that no leakages occur
11. Ensure that the stopcocks of the gas collector are closed so that the sample does not get contaminated. A leak check can be done by immersing the container into the water
12. The gas sample should be tested as soon as possible because hydrogen can rapidly diffuse through the stopcocks which causes a change in the gas composition

The figure 6.4 represents sample taking in the plant of Huatusco. On the left the very first sample is taken and in the middle the 2nd and the 3rd ones. In all three cases NaOH was used in the bottle. The last sample was taken without the solution using a bottle seen on the right. The results of the gas chromatography are presented in chapter 7.

Figure 6.4 *Collecting gas samples at the experimental pilot plant of Huatusco.*

7. RESULTS AND DISCUSSION

Chapter 7 summarizes all the results obtained in this study. In section 7.1 the results of the sensitivity analyses carried out by Thermoflex are showed and analyzed. Section 7.2 analyzes the outcomes of Thermoflex and section 7.3 the results of the engineering calculations (Excel). After that the system efficiencies and the experimentally obtained gas compositions are being discussed. Section 7.6 compares and analyzes all the results obtained in this thesis. Calculations always include some error sources and these are discussed at the end of this chapter.

7.1 Sensitivity Analysis (Thermoflex)

One objective of this study was to find out the optimal process parameters for a downdraft gasifier. The gasifier temperature, air-to-fuel-ratio, moisture content of the fuel and temperature of the pre-heated air were altered and their effect on the composition of the synthesis gas was analyzed. The results are presented in the following subsections.

7.1.1 Varying the Gasifier Temperature

The gasifier temperature was varied from 500 to 1000 °C, every 100 degrees.

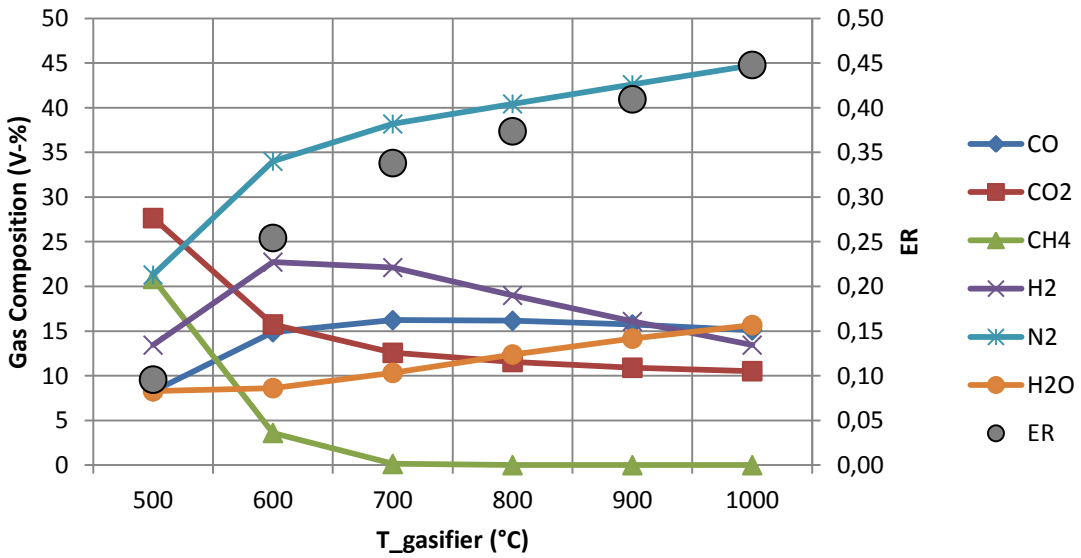

Figure 7.1 *Variation of the syngas composition and the ER with gasifier temperature (own elaboration based on the results obtained in Thermoflex).*

In figure 7.1 a decline of CH_4 and CO_2 between 500-700 °C can be observed. After that practically all the methane has been consumed and CO_2 maintains roughly a constant level. All the other fractions of components increase of which N_2 shows the steepest rise. This happens because of the increasing A/F-ratio (=meaning that the ER increases, too). At 1000 °C six times more air is being fed into the gasifier than at 500 °C so naturally the amount of N_2 increases, too. When there is more oxygen available, it would be expected that the combustion is more complete and more CO_2 would be formed. However, this kind of behavior is not seen in figure 7.1 probably because of the nature of the software (individual simulations).

If the growing ER and its effects are forgotten, the volume fractions seem rational. The fraction of CO increases affecting positively the LHV of the gas. This increase is expected within higher temperature because Boudouard reaction (equation 2.4), $C+CO_2 \leftrightarrow 2CO$, needs a certain amount of heat in order to occur (see subsection 2.3.3 and section 2.4). The reaction consumes CO_2 and produces CO which could explain their behavior in figure 7.1.

The quantity of hydrogen first increases but then starts consuming itself after 700 °C. This affects negatively the LHV of the gas. The gas would have its highest heating value at 500 °C because of the very high methane content but it has to be kept in mind that lignin (tars) needs at least a temperature of 800 °C to decompose. (Basu 2013, p.283) That is why the methane is sacrificed to reach higher temperatures, accelerate other important reactions and get rid of harmful tars.

Considering all three factors (gas composition, temperature and the ER) it seems that the optimal values are between 700-800 °C when the ER is 0.34-0.37 and the LHV of the gas 4320-3866 kJ/kg at 25 °C. However, the program does not specify if the "gasification temperature" is the temperature in the reduction zone, combustion zone, the gas exit temperature, an average of all of these or something else. Most likely it is the gas outlet temperature but there is no certainty of this.

7.1.2 Varying the Air-Fuel-Ratio (the ER)

The gas composition against the ER is illustrated in the following figure. The variation of the gasifier temperature can be seen as grey dots in the same figure. After that the figure 7.3 shows a typical behavior of the gas composition on the function of the ER.

As already explained, the gasification temperature and the A/F-ratio are dependent on each other in Thermoflex. That is why figures 7.1 and 7.2 show quite similar behavior.

Figure 7.3 illustrates a typical behavior of gas composition of woody biomass on the function of the ER. A decline in CO and an increase in CO_2 fraction can be observed. This happens because combustion is supposed to be more complete due to bigger amount of oxygen. In figure 7.2 this kind of behavior is not observed. It might happen with bigger values of the ER or it is possible that Thermoflex is not capable of simulating it.

In figure 7.2 the amounts of CO and CO_2 are even when the ER=0.27. After that the amount of CO_2 decreases and the CO increases. Thus it seems that the gasifier should maintain the ER above 0.27 but stay below 0.38. Above 0.38 the LHV of the gas is getting too low to be used in an engine-generator. These values are well within the range discussed in subsection 2.6.2 where the ER was found out to be between 0.19-0.42.

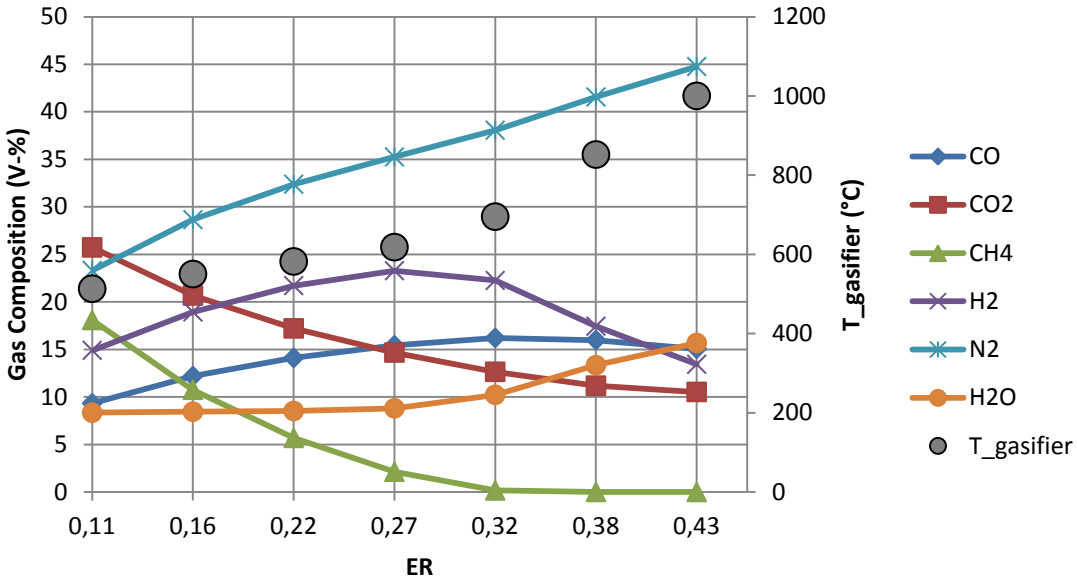

Figure 7.2 *Variation of the syngas composition and the gasifier temperature with the equivalence ratio (own elaboration based on the results obtained in Thermoflex).*

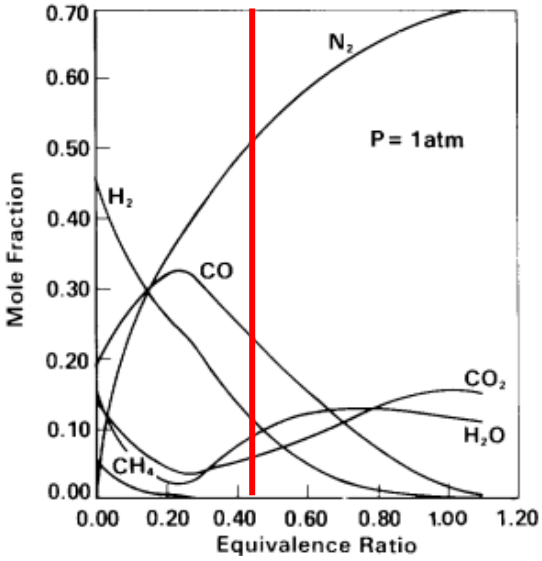

Figure 7.3 *Typical behavior of gas composition against the ER for biomass $CH_{1.4}O_{0.6}$ (adapted from Reed & Das 1988, p.26).*

7.1.3 Varying the Moisture Content of the Fuel

In these simulations the moisture content was varied between 0 and 25 w-%, the temperature was fixed at 800 °C and the A/F-ratio was initially set to 1.76 but it started to

lower slightly within the simulations (see declining values of N_2). The software did not allow any higher moisture content to be simulated but according to literature (Reed & Gaur 2001, p.1-13) 20 % is roughly the recommended limit for downdraft gasifiers so no further simulations are needed.

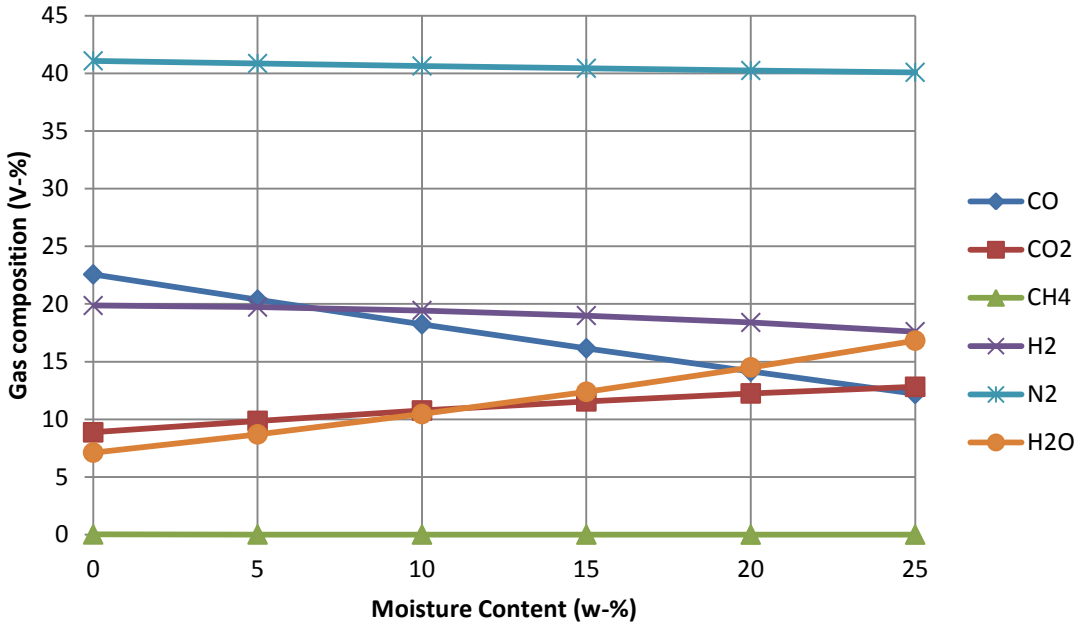

Figure 7.4 *Variation of the syngas composition with the moisture content of bamboo (own elaboration based on the results obtained in Thermoflex).*

The figure 7.5 shows a literature reference for the bamboo gas composition against the moisture content.

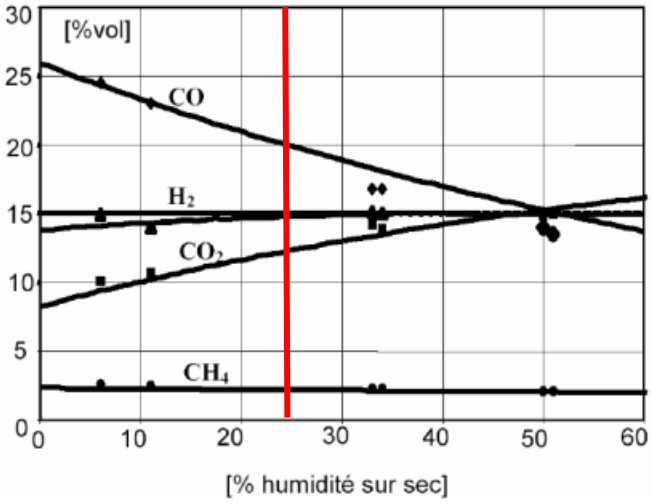

Figure 7.5 *Variation of the syngas composition with the moisture content of bamboo (Kerlero de Rosbo & Bussy 2012, p.36)*

It can be seen that the quality of the syngas worsens within the moisture content. A decline in CO and an increase in CO_2 can be observed and thus the LHV decreases. Naturally the fraction of H_2O also rises when the feedstock is moister.

All this is in line with the results found in the literature. A similar behavior in figures 7.4 and 7.5 can be seen: when the moisture content is between 0 and 25 % the fraction of CO declines approximately 10 percentage points in figure 7.4 and 6 percentage points in figure 7.5. At the same time the fraction of CO_2 rises 4 percentage points in both cases and also the other fractions act similarly.

According to figure 7.4 the ideal moisture content would be 0 %. That is when the gas would have its highest heating value. However, 0 w-% is not very practical because bamboo would need heavy drying to evaporate all the humidity it contains when it is fresh (up to 45 %) and that would be energy and time consuming. A small amount of water is also needed as steam to react with volatiles and char and to take part in the water-gas reaction (equation (2.5)) that produces hydrogen. Thus 0 % is not convenient for the process. With reasonable effort the moisture content can be reduced to 10-15 % which is considered as a suitable amount of humidity in the fuel according to the sensitivity analysis and literature. Thus 15 % will be taken as the optimal value.

7.1.4 Varying the Temperature of the Pre-heated Air

In the last sensitivity analyses the temperature of the pre-heated air was altered between 50 and 600 °C. The gasifier temperature also started to change which can be seen as grey dots in figure 7.6.

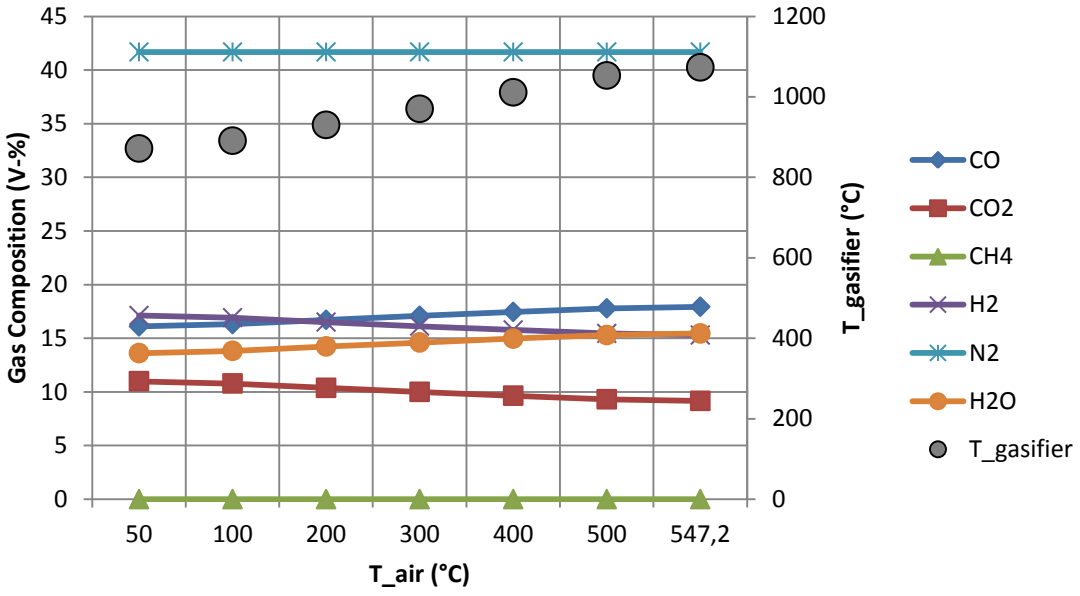

Figure 7.6 *Variation of the syngas composition and gasifier temperature with the air temperature (own elaboration based on the results obtained in Thermoflex).*

It can be observed in figure 7.6 that the composition of the gas hardly changes. A moderate increase in CO and a decrease in CO_2 can be seen but the effect on the LHV is minimal. The temperature inside the gasifier rises within the air temperature. When try-

ing to increase the air temperature to 600 °C, the software only let it rise up to 547.2 °C. At this point the gasifier temperature was already at 1073.1 °C and the simulation did not run any further. 1000-1100 °C might be a maximum limit for the temperature set by the software.

Although there are no big changes in the gas composition according to figure 7.6 there might be other advantages that could be obtained through pre-heating. When the gasifier is ignited, it takes a certain time before the process becomes steady. The temperature needs to rise so that the bamboo is dried, all the essential reactions occur and tars are decomposed. The pre-heated air could speed up these processes and help to establish the process in shorter time. This would be beneficial for the equipment if the amount of tars could be decreased. The system could also achieve better overall system efficiencies when heat is recycled, not wasted. However, according to figure 7.6 no recommended range for temperatures can be given. The effect of pre-heated air should be investigated using different software or observing the process in practice.

7.1.5 Summary

The results and discussion in the previous subsections show that the optimal range for the different parameters would be the following:

- gasifier temperature between 700-800 °C,
- the A/F-ratio between 1.25-1.75 (ER=0.27-0.38) and
- the moisture content of bamboo between 10-15 w-%.

The effect of the pre-heated air could not be figured out completely by using Thermoflex.

7.2 More Detailed Thermoflex Simulation

The most important results of the more detailed simulation are listed in table 7.1 below. More results can be found in Appendix 3, in table A3.1.

Table 7.1 *Results of Thermoflex simulation (IIE 2014a).*

Variable	Thermoflex	Unit
Mass flow of bamboo	62.9	kg/h
Feeding air	109.10	kg/h
ER	0.347	-
Synthesis gas flow	162/197	m^3/h
LHV (gas)	3866/4957	kJ/kg
Cold gas efficiency	75.62	%

The LHV of Thermoflex is given at 25 and at 800 °C, respectively. The difference is the sensible heat that is being lost when the gas is cooled down.

The syngas composition, obtained in the simulation, is presented in table 7.2. It is the raw gas composition which means that the gas has not passed through the cleaning system yet. That is why it still contains traces of acid compounds such as H_2S and COS. It can also be seen that hydrogen and carbon monoxide form only 35 % of the gas and the rest has no heating value.

Table 7.2 *The syngas composition obtained in the Thermoflex simulation (IIE 2014a).*

Compound	**Thermoflex vol-%**
CO	16.15
CO_2	11.55
CH_4	0.0056
N_2	40.43
H_2O	12.38
H_2	18.99
H_2S	0.0048
COS	0.0002
Ar	0.4863
Σ	**100.00**

7.3 Engineering Calculations

The step-by-step calculations are presented in Appendix 4. The results obtained in STP and in Huatusco's conditions are listed in table 7.3 below.

The different pressure and temperature in Huatusco have an effect on the moist in the air that increases from 0.36 % (at STP) to 1.17 % (in Huatusco). If temperature rises up to 25 °C, there will be 2.2 % of water in the air. The increased amount of water can be seen as a small increase in the amount of air (108.64 kg/h vs. 109.19 kg/h).

When temperature rises and air pressure decreases, the gas is less dense and occupies a bigger volume. Hence more gas is produced by the same amount of bamboo. At the same time the heating value of the gas decreases because the fuel has larger volume per energy unit. The cold gas efficiency remains basically unchanged because the increased gas flow "replaces" the lost heating value (see section 5.6 for the calculation of efficiencies).

Table 7.3 *The results of the basic engineering calculations in STP and in real conditions of Huatusco, Veracruz (own elaboration).*

Variable	Unit	Results in STP	Results in Huatusco's conditions
Air to Fuel ratio (stoichiometric)	kg air/kg bamboo	4.62	4.64
Air to Fuel ratio (actual)	kg air/kg bamboo	1.73	1.74
Feeding air	kg/h	108.64	109.19
Gas to Fuel ratio	$(N)m^3$ gas/kg bamboo	2.53	3.10
Synthesis gas flow	$(N)m^3/h$	**159.44**	**195.11**
Fuel to Electricity	kg bamboo/kWh	1.42	1.43
Mechanical output (engine)	kW	53.13	53.05
Electrical output (engine)	kW	45.69	45.62
LHV (gas)	$kJ/(N)m^3$	4284.11	3495.75
Cold gas efficiency	%	66.50	66.39

The following table 7.4 below presents the syngas composition in both conditions based on the atomic balance Excel calculations showed in Appendix 4.

Table 7.4 *The calculated syngas compositions (own elaboration).*

Compound	STP vol-%	Huatusco vol-%
CO	16.49	16.36
CO_2	12.24	12.14
CH_4	0.0015	0.0015
N_2	41.53	41.18
H_2O	9.33	10.09
H_2	20.40	20.23
H_2S	0.00	0.00
Σ	**100.00**	**100.00**

It can be seen that the gas composition barely changes when the ambient pressure and temperature vary. The fraction of H_2O increases because of the higher amount of water in the air and this slightly dilutes the syngas.

7.4 The System Efficiencies

Reference values for cold gas efficiencies can be seen in table 7.5 below. According to different literature sources it can be stated that the cold gas efficiency calculated in section 5.6 is in the normal range.

Table 7.5 *Cold gas efficiencies reported in the literature.*

Reported Cold Gas Efficiency	Reference
62.90-73.20 %	Gunarathne 2012
45.00-80.91 %	Other research groups mentioned in Gunarathne 2012
55.19-70.40 %	Garg & Sharma 2013
60-75 %	FAO 1986
66.50 %	Own elaboration

The overall system efficiency obtained in section 5.6 was **16.00 %**. Garg & Sharma (2013, p.4) report values between **13.89 and 17.7 %** and FAO (1986, p. 108) **15-20 %** for the overall system efficiency so again the value obtained in this study seem to be in the normal range.

7.5 Results and Analysis of the Gas Chromatography

The gas samples that were collected on the field (see chapter 6) were analyzed using gas chromatography in the Geothermal energy laboratory of the Electrical Research Institute, in Cuernavaca Mexico during the fall of 2014. The chromatograph applied was model Agilent 7890A by Agilent Technologies. The moisture contents of bamboo were defined in subsection 3.2.1 and their average values are used in this context. The results are listed in table 7.6 below. The column "Other" contains at least water, carbon dioxide and tars.

As seen in the table, the first sample was unsuccessful. There was a strong suction in the hose where the sample was taken from and the vacuum inside the sampling bottle was not strong enough to drag the gas out of the hose. That is why the ambient air was sucked into the hose and also into the bottle. A vacuum pump should have been used to force the gas to enter the container.

Table 7.6 *Results of the gas chromatography.*

Sample nro	H_2 v-%	O_2 v-%	N_2 v-%	CO v-%	CH_4 v-%	Other v-%	Total v-%	Bamboo	MC w-%
1	n/d	21	79	n/d	n/d	n/d	100	Bambusa Old Hamii Munro	15.13
2	3.1	11.3	67.4	6.4	0.49	11.31	100	Bambusa Vulgaris Vitata	14.06
3	4	12	69	7.1	0.51	7.39	100	Bambusa Vulgaris Vitata	14.06
4	11	10	52	14	0.51	12.49	100	Bambusa Vulgaris Vitata	13.42

The second and the third sample were taken at the gas outlet where the blower was blowing gas out of the hose. This was done to avoid the air to get sucked into the system. However, the results show that there is still a lot of air leaking in at some point of the gas trajectory. The synthesis gas is not supposed to contain oxygen at all. The gas should, however, contain CO_2 but it could not be separated from the sample probably because it reacted with NaOH. That is why the last sample was taking without the NaOH-solution.

The last sample shows the best results so far. Nevertheless, there is still a significant quantity of oxygen so more improvements in the trajectory have to be done in order to block the air leakages. Hydrogen and carbon monoxide levels are significantly higher than in other samples, which is positive, but for some reason the CO_2 could not be detected in this sample either although there was no NaOH-solution in the bottle. As a summary, it can be stated that a lot of progress can be seen in the results but there is still work to be done to reach the gas composition that was obtained in the simulations and calculations.

7.6 Comparison of the Results

The following table 7.7 compares the results obtained in Thermoflex simulation (section 7.2) and Excel calculations (section 7.3). The lower heating value in Thermoflex is 3866 kJ/kg but converting the units it equals to 3261.92 kJ/m^3 (at 25 °C and 88,100 Pa, M=23.74 g/mol) and to 4097.19 kJ/Nm^3 (standard conditions). Notice that the LHV obtained in Excel is now also reported at 25 °C (not at 15 °C like earlier in table 7.3).

Table 7.7 *Comparison of the results.*

Variable	Unit	Thermoflex	Excel
Mass flow of bamboo	kg/h	**62.9**	**62.9**
Feeding air	kg/h	109.10	109.19
ER	-	**0.347**	**0.347**
Synthesis gas flow	m^3/h	196.67	195.11
	Nm^3/h	162.10	159.44
LHV (gas)	kJ/m^3	3261.92 (25 °C)	3378.51 (25 °C)
	kJ/Nm^3	4097.19	4284.11
Cold gas efficiency (25 °C)	%	75.62	64.16

The mass flow of bamboo and the ER were used as initial values so that is why they are exactly the same in both cases. The other results were obtained through simulations and calculations. It can be seen that the results are very congruent except for the cold gas efficiency. The reason for this is the difference in the heating values of bamboo. In the Excel calculations a value obtained in a laboratory on a dry basis (see subsection 3.5.1) was used while Thermoflex calculates the value based on the composition of

bamboo and it includes moisture and ash (see Appendix 3, figure A3.3). The value obtained in the laboratory is 3904 cal/g which equals to 16,334 kJ/kg but the value defined by Thermoflex is only 13,957 kJ/kg. If Thermoflex' value was used in Excel, the cold gas efficiency would be as high as 75.09 % (at 25 °C).

According to Basu (2013, p. 275) the normal range for the lower heating value is 4000-7000 kJ/Nm^3 when air is used as a gasification medium. Reed & Das (1988, p. 24) report a little bit higher values between 4880 and 7320 kJ/Nm^3 and Gunarathne (2012) obtained results between 4650 and 4770 kJ/Nm^3. The heating values obtained in this study, 4097.19 and 4284.11 kJ/Nm^3, are in the range set by Basu but lower than the other reported results. As a comparison, the lower heating value for natural gas is approximately 36,626 kJ/Nm^3 (Boundy et al. 2011, p. 201) which makes it more than 8 times higher than that of the synthesis gas. This affects greatly the output of the gas engine (see subsection 5.1.2).

The following table 7.8 compares the gas compositions obtained in this study with values found in the literature. Some of the literature values are reported on a dry basis and that is why the Excel results were converted on a dry basis, too. The results on a wet basis can be seen in table 7.4 in section 7.3.

Table 7.8 *Obtained syngas compositions compared with literature references.*

	Bamboo, Thermoflex[1] (vol-%)	**Bamboo, Excel[2] (vol-%)**	**Bamboo, Measured[3] (vol-%)**	**Bamboo, Literature[4] (mol-%)**	**Bamboo, Literature[5] (mol-%)**	**Wood, Literature[6] (mol-%)**
H_2	18.99	22.50	11	16-20	15-18	12-20
H_2O	12.38	(dry)	*N/r*	2	(dry)	(dry)
N_2	40.43	45.80	52	39.5-52.5	47-52	50-54
CO	16.15	18.19	14	18-22	20	17-22
CO_2	11.55	13.50	*N/r*	10-14	10-12	9-15
CH_4	0.0056	0.0015	0.51	1.5-2.5	3	2-3

[1]Thermoflex Simulations; [2]Own Calculations in Excel; [3]Own measurements; [4] NMBA 2007, p.1; [5] Kerlero de Rosbo & de Bussy 2012, p.35; [6] FAO 1986, p.18

When talking about ideal gases the volume fraction and the mole fraction are considered the same so the values of table 7.8 are comparable with each other. It can be seen that the fraction of nitrogen is always very high, roughly between 40 and 50 %. Nitrogen has no heating value so it is an unwanted but unavoidable compound in the synthesis gas resulting from the usage of air as a gasification agent. Hydrogen, carbon monoxide and methane are the most important compounds affecting the heating value of the gas.

The fraction of hydrogen obtained in Thermoflex simulations and in Excel calculations might be slightly too optimistic compared with the literature references. The fraction of CH_4 then again is very low which has a negative influence on the LHV of the gas. The amount of nitrogen is in the reported range. The fraction of CO seems to be a

little bit low but still acceptable and the amount of CO_2 coincides with the literature values. Thus it can be stated that both Thermoflex and the Excel calculations give fairly reliable results and that the synthesis gas could be used to fuel an ICE. The gas composition of wood also seems to be very close to the composition of bamboo.

The gas chromatography results (own measurements) are still far behind the simulated, calculated and reference values. It means that the process is not yet well controlled and improvements are needed. The amount of nitrogen seems to be normal but this sample contained 10 % of oxygen (see table 7.6) so also part of the nitrogen leaked in at some point of the gas trajectory. The amount of methane is higher than in the simulations but lower than in the literature references. An increase of a few percentage points in the amounts of hydrogen and carbon monoxide is also needed before the gas could be used in an ICE.

7.7 Possible Sources of Error

Different assumptions and generalizations cause errors in the calculations. The construction of the gasification plant has not been finished yet so the validity of the results cannot be completely proved because of lack of measured data.

Thermoflex utilizes thermodynamic equilibrium models (heat balances) to carry out the simulations. (Thermoflow 2014). Each simulation is individual so the user gets a series of "still-pictures" about the gasifier behavior. Continuous performance cannot be simulated. For example in sections 7.1.1-7.1.4 from six to seven different simulations were needed in each case. The equilibrium is reached in an infinite time and that is why the software might give ideal yields as results. In practice, only a limited time is available for the reactions and it depends e.g. on the reaction rates how well the reactants turn into products. (Basu 2013, p.233.) Hence, the results obtained in the software might be too optimistic.

Thermoflex uses different components that already exist commercially. The idea is to connect these components and examine the behavior of the whole system. A downdraft gasifier exists in the component library but the program does not give any information for instance about its geometry. The gasifier used in Huatusco is designed by the Electrical Research Institute and is not a commercial model yet. Thus using a different kind of gasifier might cause some inaccuracies in the results. Also the program does not specify what the "gasification temperature" exactly means. It might be the temperature in the reduction zone, combustion zone, the gas exit temperature, an average of all of these or something else. Most likely it is the gasifier outlet temperature because the optimal values obtained in this thesis were between 700 and 800 °C which would be too low for the combustion/reduction zones of the gasifier.

The ambient conditions used in the simulations and calculations were partly measured in Huatusco and partly checked in weather forecasts. Obviously every day is different and the air temperature and the relative humidity can vary a lot. The results of

this thesis only represent certain conditions so they are expected to vary according to the weather changes.

The engineering calculations elaborated for this study, assume a hundred percent carbon conversion rate and that all the reactions are complete. That is why the results of the simulations and calculations are very congruent but do not necessarily directly correspond to the real processes.

The experimental results obtained in this thesis also contain some uncertainties. The gas samples were collected on the field using the experimental gasifier in Huatusco, Veracruz. The samples were first brought to the Electrical Research Institute in Cuernavaca (a six to seven hour drive) to be analyzed and it took several days before they got analyzed. According to Reed & Das (1988, p. 62) the hydrogen of the sample can already diffuse in a few hours. Therefore it is hard to know if the waiting time affected the results, if some errors were made on the field when collecting the samples or if the process simply does not work the way it should.

8. CONCLUSIONS

Mexico has committed to increase the share of renewable energy in its energy mix and to decrease the CO_2 emissions during the upcoming years and decades. Another challenge is to provide the whole country with an access to electricity and to respond to increasing need of energy without accelerating the climate change. Wind and solar energy are already relatively widely spread technologies but there are also other, alternative ways to produce renewable energy. One of them is gasification of biomass which was investigated in this thesis.

A wide range of different fuels can be gasified. In this study, the biomass in question was bamboo that grows in the plantations of Huatusco, in the state of Veracruz Mexico. Bamboo is closer to wood qualities than grass qualities although it belongs to the family of grass plants. Chapter 3 showed that the heating value of bamboo is lower than that of wood but bamboo grows really fast making it an intriguing option for a fuel. The ability of bamboo to accumulate biomass beats even eucalyptus which is famous for its fast growing rate.

Some thermochemical characteristics of bamboo are not yet so well-known because it has traditionally been a construction material, not a fuel. To understand better the behavior of bamboo in a gasifier, its porosity, reaction rates and performance in high temperatures should be further investigated. Also the affect of the size of bamboo chips would be an interesting target for investigation. Nevertheless, bamboo seems to be a promising fuel for gasification because of its acceptable heating value, low ash and sulfur contents. There is little variation between different bamboo species but according to this study Dendrocalamus Strictus, Dendrocalamus Asper and Bambusa Old Hamii Munro seem to have the best qualities for gasification. From these species Bambusa Old Hamii Munro has the best availability (most hectares) in Huatusco at the moment.

Another objective of this study was to find out the optimal process parameters for a fixed bed downdraft gasifier. The sensitivity analysis carried out in chapter 5 (results shown in chapter 7) by using Thermoflex gave reasonable results for the optimal range of gasification temperature, air-fuel-ratio and the moisture content of the fuel. The results are all in line with the literature references. Also the effect of pre-heated air on gas composition was simulated but it was not possible to make trustworthy conclusions based on the results. The higher air temperature probably improves the process stability and decreases the quantity of tars but that could not be proved by the simulation. Thus, further investigation either on the field or using different software is recommended.

Indeed different, more complicated software could be useful in the simulation of gasification processes. Thermoflex asks for inputs and gives outputs without revealing

what happens inside the gasifier. Instead of a program that uses heat balances, Computational Fluid Dynamics (CFD) might offer a tool to understand what is actually occurring in the processes and how different variables affect them. However, the licenses of these programs are pricy and one needs a higher level of specialization in order to use them well. Thermoflex is simpler to use and it seems to give rather rational results. It also simulates the behavior of the whole system including gas conditioning equipment and the engine-generator which then again cannot be done by CFD.

Because of the nature of a pilot project, a lot of knew know-how was acquired through trial and error. This takes a lot of time, delays the project and usually costs a lot of money. That is also why a realistic CFD-model of the gasifier would be helpful. Now several test runs utilizing a small scale experimental gasifier were done and four gas samples taken to examine the gas composition. However, the experimental gasifier was originally only meant to be a miniature and that is why it was made of cheaper material and for example no proper insulation exists. With that device it is probably not possible to reach as high temperatures as would be needed to obtain good quality gas. Thus the results are only preliminary and more tests need to be done and samples taken when the construction of the real gasification plant is finished. This will unfortunately happen outside of the time frame of this thesis.

Also, more equipment for measuring different variables of the gasification process is needed. It is sometimes challenging to find trustworthy suppliers in Mexico and searching and buying gear abroad is complicated and takes more time. For this reason e.g. the temperatures inside the gasifier could not be measured in this thesis. Continuous gas sampling would be advantageous because now there is no way to know if the process is stable or not. Also, if modifications are done, it is hard to tell how they affect the gas composition or if there is any effect at all.

When the pilot plant is finished, long-lasting, uninterrupted test runs are needed and stable production of good quality gas has to be obtained before the gasifier can be connected with the genset. Also the tar content of the synthesis gas needs to be tested before turning on the engine so that it does not get damaged. Tars are hard to clean from the engine parts and they can destroy the whole device which will be very expensive.

If the gasification process discussed in this thesis turns out to be successful, it will have a positive influence on the whole area of Huatusco. The most important benefits include regional employment creation and strengthening of the local economy, cleaner electricity production, smaller dependency on the fuel import and contribution to the prevention of climate change and erosion. Gasification might be an answer for some remote areas, where no power grid exists, to provide electricity but that requires a suitable biomass and efforts from several different parties to support the local people with the required know-how.

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APPENDIX 1: THE REACTION KINETICS FOR BOUDOUARD REACTION

The reaction rate constant can be expressed in Arrhenius form as follows:

$$k_i = A_0 e^{-\frac{E}{RT}} \tag{A1.1}$$

where
A_0 = pre-exponential constant [1/s]
E = activation energy for the reaction [kJ/mol]
R = the universal gas constant [kJ/mol K]
T = reaction temperature [K]

It can be seen that the reaction rate constant is dependent on temperature but not on the concentration of the components.

The apparent gasification rate for the Boudouard reaction, also known as the Langmuir-Hinshelwood rate, can be expressed as follows:

$$r_b = \frac{k_{b1} * P_{CO2}}{1 + \left(\frac{k_{b2}}{k_{b3}}\right) * P_{CO} + \left(\frac{k_{b1}}{k_{b3}}\right) * P_{CO2}} \tag{A1.2}$$

where
P_{CO} = partial pressure of CO on the char surface
P_{CO2} = partial pressure of CO_2 on the char surface
k_i = reaction rate constants (see equation A1.1).

The equation (A1.2) takes into account the inhibiting effect of CO. Without the CO inhibition the same equation can be written in a simpler form:

$$r_b = A_b * e^{-\frac{E}{RT}} * P_{CO2}^m \tag{A1.3}$$

where
A_b = pre-exponential constant [1/s]
E = activation energy [kJ/mol]
R = the universal gas constant [kJ/mol K]
T = reaction temperature [K]
P_{CO2} = partial pressure of CO_2 on the char surface
m = reaction order with respect to the gas partial pressure. (Basu 2013, p.223.)

Partial pressures of different components can be calculated according to Dalton's Law when the total pressure and the composition of the gas are known. In this case the total pressure is expected to be the normal air pressure 1.01325 bar and the composition of the gas is obtained by a Thermoflex simulation.

Table A1.1 *The partial pressures of different gas components (own elaboration).*

Compound	w-%	p_i (bar)
H_2	19.90	0.202
H_2O	7.17	0.073
N_2	43.20	0.438
CO	16.81	0.170
CO_2	12.40	0.126
CH_4	0.0015	0.000
H_2S	0.0001	0.000
Ar	0.52	0.005
Σ	100.00	1.013

Table A1.2 gives values for E and A to calculate k_{b1}-k_{b3} and thus obtain the reaction rates when CO inhibition is taken into account (using equations (A1.1) and (A1.2)). Table A1.3 gives values for E, A and n to calculate the reaction rates without the CO inhibition (using the equation (A1.3)).

Table A1.2 *Values for activation energy and pre-exponential factor for birch char when CO inhibition is considered. (Basu 2013, p.224)*

	Rate Constant (1/s bar)	E (kJ/mol)	A (1/s bar)
Betula (Birch)	k_{b1}	165	130,000
	k_{b2}	20.8	0.36
	k_{b3}	236	32,300,000

Table A1.3 *Values for activation energy, pre-exponential factor, reaction order for different wood chars when CO inhibition is not considered. (Basu 2013, p. 224)*

	E (kJ/mol)	A (1/s bar)	m
Pseudotsuga menziesii (Douglas fir)	221	1,967,000,000	0.6
Betula (Birch)	215	3,100,000	0.38

The results are listed in the following tables A1.4 and A1.5. Graphs of the results are presented in section 2.4.

Table A1.4 *The reaction rates for Boudouard reaction for birch char (own elaboration).*

T (°C)	T (K)	k_{b1}	k_{b2}	k_{b3}	r_b (1/s)
300	573.15	1.1911E-10	0.004577	1.00072E-14	1.92093E-22
400	673.15	2.04137E-08	0.008754	1.56882E-11	2.69853E-17
500	773.15	9.24713E-07	0.014158	3.6667E-09	1.76656E-13
600	873.15	1.74887E-05	0.020509	2.45705E-07	1.54449E-10
700	973.15	0.000181	0.027530	6.93821E-06	3.33941E-08
800	1073.15	0.001209	0.034982	0.000105	2.56912E-06
825	1098.15	0.001842	0.036889	0.000192	6.62396E-06
850	1123.15	0.002754	0.038808	0.000341	1.61821E-05
900	1173.15	0.005848	0.042672	0.001002	8.17669E-05
925	1198.15	0.008324	0.044614	0.001660	0.000168
950	1223.15	0.011678	0.046559	0.002694	0.000327
1000	1273.15	0.022085	0.050454	0.006703	0.001029
1025	1298.15	0.029818	0.052399	0.010298	0.001680
1050	1323.15	0.039804	0.054343	0.015566	0.002610
1100	1373.15	0.068725	0.058216	0.033997	0.005586
1125	1398.15	0.088992	0.060144	0.049200	0.007789
1150	1423.15	0.114193	0.062064	0.070284	0.010592
1200	1473.15	0.183315	0.065880	0.138313	0.018460

Table A1.5 *The reaction rates of Boudouard reaction for birch and douglas fir without CO inhibition (own elaboration).*

T (°C)	T (K)	r_b (1/s) Birch	r_b (1/s) Douglas fir
300	573.15	3.5815E-14	4.08778E-12
400	673.15	2.9175E-11	4.01475E-09
500	773.15	4.197E-09	6.63451E-07
600	873.15	1.9345E-07	3.40314E-05
700	973.15	4.058E-06	0.00078
800	1073.15	4.8275E-05	0.00991
825	1098.15	8.3554E-05	0.01741
850	1123.15	0.00014	0.02984
900	1173.15	0.00038	0.08182
925	1198.15	0.00060	0.13128
950	1223.15	0.00093	0.20660
1000	1273.15	0.00213	0.48506
1025	1298.15	0.00314	0.72514
1050	1323.15	0.00458	1.06769
1100	1373.15	0.00934	2.21892
1125	1398.15	0.01307	3.13666
1150	1423.15	0.01809	4.38039
1200	1473.15	0.03352	8.25721

APPENDIX 2: THE CALORIMETRIC VALUES OF HUATUSCO BAMBOO SPECIES

Table A2.1 *Heating values of different bamboo species (IIE 2012a; IIE 2012b).*

Name	Higher heating value (cal/g)			Lower heating value (cal/g)			LHV (MJ/kg)	HHV (MJ/kg)
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	Average	Average
Bambusa Old Hamii Munro	4316	4444	4502	4003	4135	4193	17.20	18.50
Bambusa Vulgaris Vitata	4203	4418	4423	3904	4101	4118	16.91	18.19
Bambusa Vulgaris Schrader	4252	4430	4481	3946	4122	4173	17.07	18.36
Dendrocalamus Strictus	4315	4537	4540	4011	4224	4230	17.38	18.68
Dendrocalamus Asper	4478	4403	4450	4173	4095	4140	17.31	18.59

APPENDIX 3: THERMOFLEX SIMULATION

Figure A3.1 *The process flowchart of the gasification plant (IIE 2014a).*

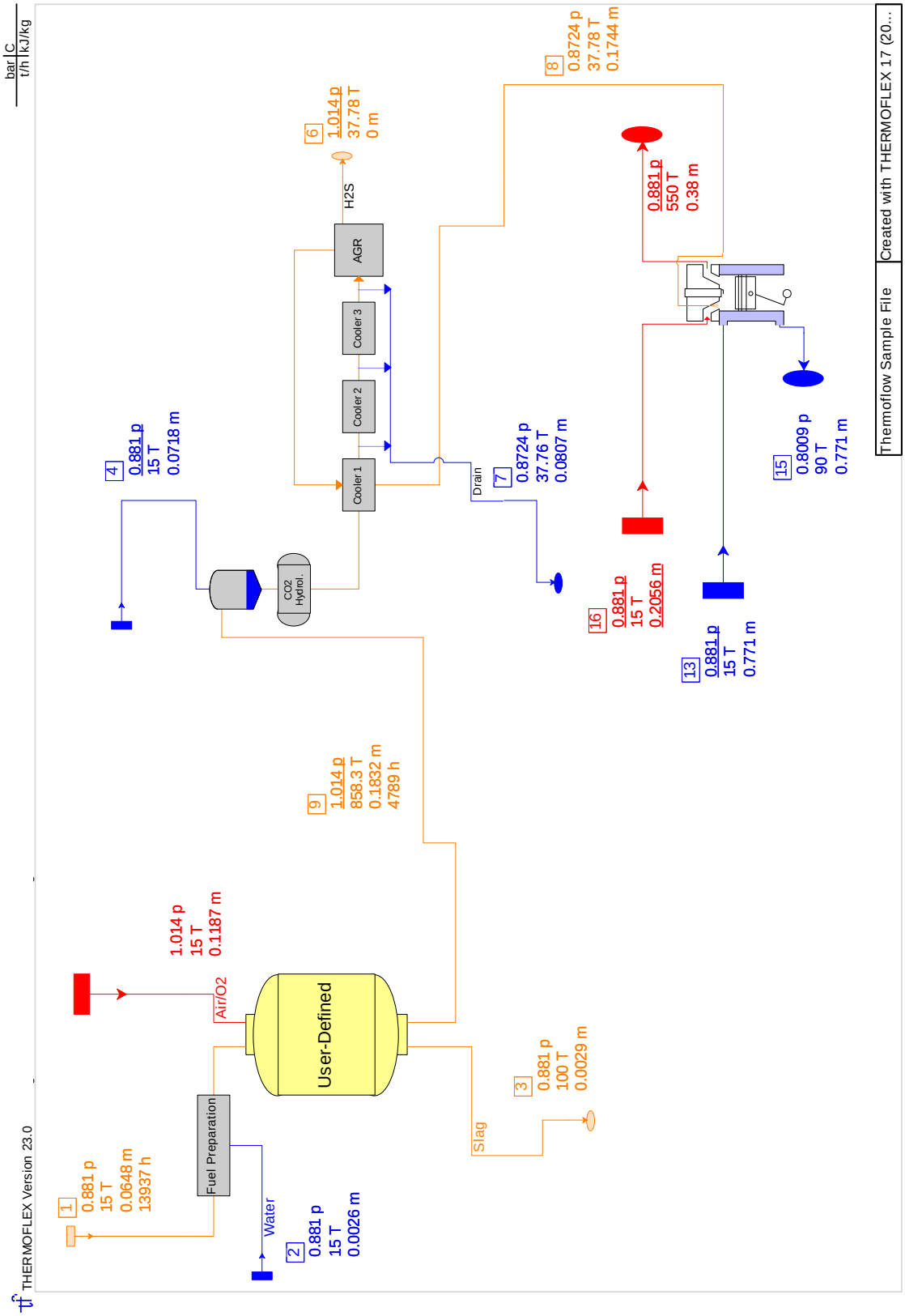

Figure A3.2 *The gasifier unit inputs and outputs (IIE 2014a).*

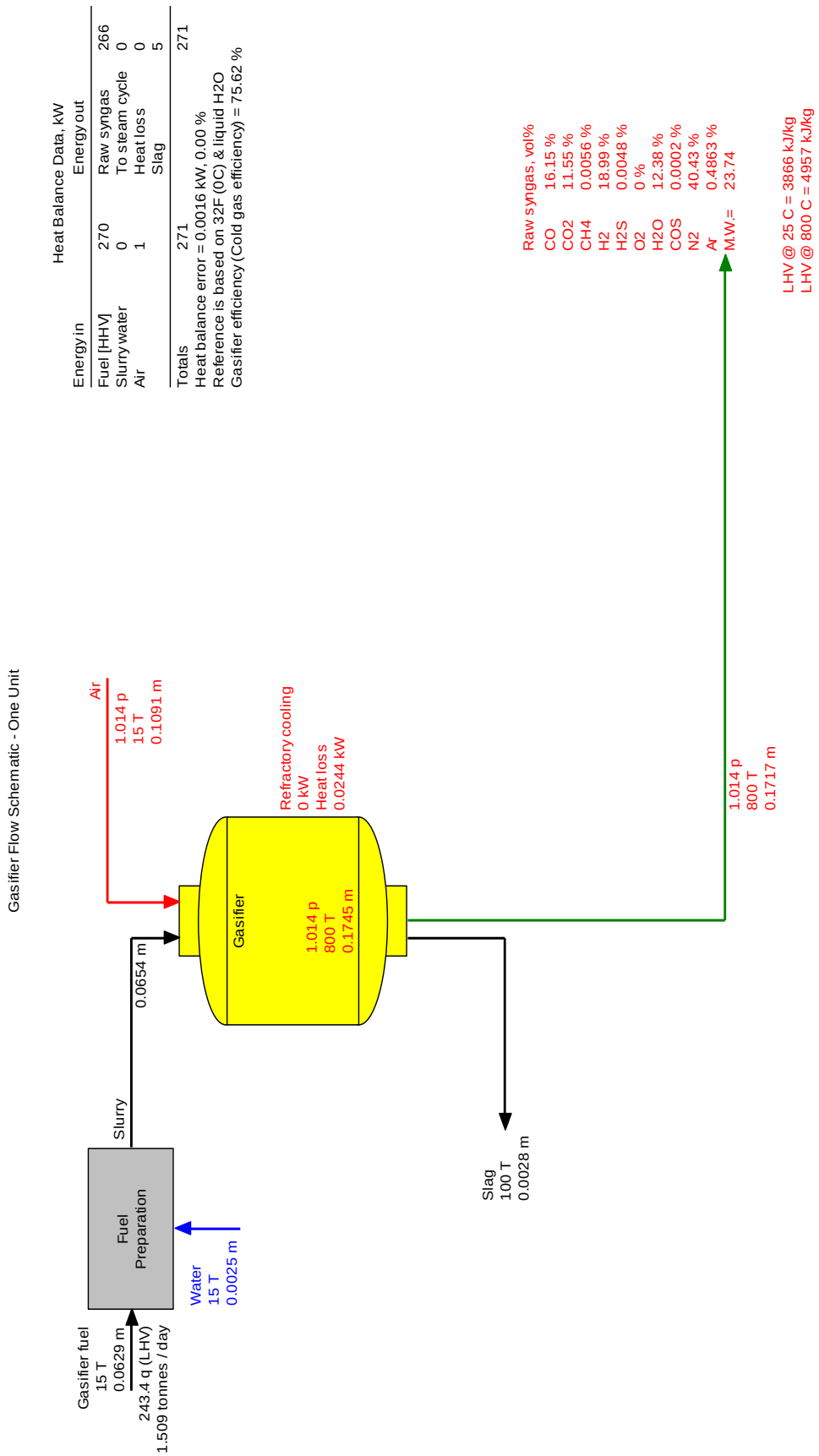

Table A3.1 *Thermoflex simulation, inputs and outputs of the gasifier (IIE 2014a).*

Off-design Heat Balance Results		
Gasifier(user-defined)[1]		
Number of units in operation	1	
Number of units in plant	1	
Gasifier pressure	1.014	bar
Gasifier temperature	800	C
Gasifier efficiency (Cold gas efficiency), (M*LHV)_Syngas / (M*LHV)_Fuel, @ 77F/25C	75.62	%
Gasifier Fuel		
Temperature	15	C
Mass flow	0.0629	t/h
Composition (wet, ash free):		
Carbon (C)	24.9	atomic %
Hydrogen (H)	50.87	atomic %
Oxygen (O)	24.15	atomic %
Nitrogen (N)	0.0782	atomic %
Sulphur (S)	0.0043	atomic %
Ash in fuel	3.684	weight %
LHV @ 25C (moisture and ash included)	13957	kJ/kg
Fuel preparation power requirement	1.386	kW
Air		
Pressure	1.014	bar
Temperature	15	C
Mass flow	0.1091	t/h
Composition:		
Oxygen (O2)	20.71	vol %
Carbon Dioxide (CO2)	0.03	vol %
Water (H2O)	1.136	vol %
Nitrogen (N2)	77.19	vol %
Argon (Ar)	0.9297	vol %
Slurry Water		
Pressure	0.881	bar
Temperature	15	C
Enthalpy	63.02	kJ/kg
Mass flow	0.0025	t/h
Quench water		
Temperature	100	C
Mass flow	0	t/h

Hot Raw Syngas		
Pressure	1.014	bar
Temperature	800	C
Mass flow	0.1717	t/h
Molecular weight	23.74	
Composition:		
Carbon Monoxide (CO)	16.15	vol %
Carbon Dioxide (CO2)	11.55	vol %
Methane (CH4)	0.0056	vol %
Hydrogen (H2)	18.99	vol %
Hydrogen Sulfide (H2S)	0.0048	vol %
Oxygen (O2)	0	vol %
Water (H2O)	12.38	vol %
Carbonyl Sulfide (COS)	0.0002	vol %
Nitrogen (N2)	40.43	vol %
Argon (Ar)	0.4863	vol %
LHV @ 25C	3866	kJ/kg
Refractory cooling	0	kW
Heat loss from gasifier	0.0244	kW
Slag		
Temperature	100	C
Mass flow	0.0028	t/h
Unburnt C in slag	17.49	%
Slag quench heat rejection (cooled to 100C)	0.4569	kW

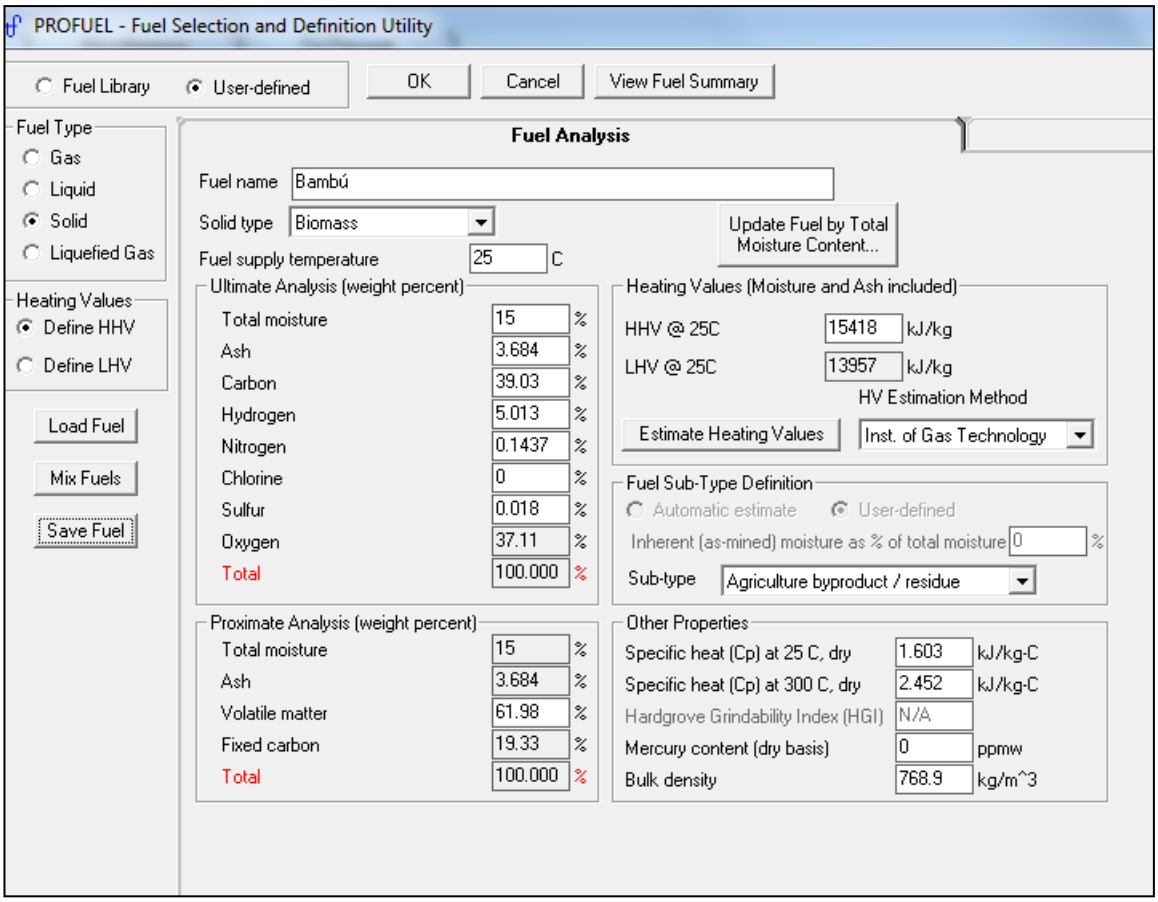

Figure A3.3 *The characteristics of bamboo used in Thermoflex, moisture and ash included (IIE 2014a).*

APPENDIX 4: ENGINEERING CALCULATIONS FOR A DOWN-DRAFT GASIFIER

All the calculations in this appendix are done by following the examples of Raiko et al. (2002), Huisman (2000) and Cuba (2011). This appendix shows step-by-step calculations in STP-conditions. The results for Huatusco's conditions have been obtained by similar calculations but using the temperature of 15 °C and air pressure of 881 mbar which affect e.g. the moisture content of the air and the volume of the gas.

The initial values for the calculations are:

Humidity of bamboo	15 %
Mass flow of bamboo = F	63.7 kg/h
ER	0.374

These values were also used in the simulation of Thermoflex (see Appendix 3). Now they are used again in the calculations elaborated for this thesis to make sure their reliability.

Stoichiometric Combustion of Bamboo

The amount of water vapor in the air, which is used for burning, needs to be calculated first. There are various empirical formulas for defining the pressure of saturated vapor (ph') but in this study it was read in a table at Taulukot.com. All the calculations are done in standard conditions for temperature (273.15 K or 0 °C) and pressure (1 atm).

Table A4.1 *The variables used in the calculations (STP-conditions).*

Symbol	Name	Value	Unit
Ψ	Relative humidity of air	60	%
T	Temperature	273.15	K
p	Air pressure	1013.25	mbar
ph'	Pressure of saturated vapor	6.105	mbar (at 273.15 K)[1]

[1]Taulukot.com

The partial pressure of vapor in the air can be calculated when the relative humidity and the pressure of saturated vapor are known:

$$\Psi = \frac{\mathrm{ph}}{\mathrm{ph}'} \rightarrow \mathrm{ph} = \Psi * \mathrm{ph}' = 0.60 * 6.105\ \mathrm{mbar} = 3.663\ \mathrm{mbar} \qquad \text{(A4.1)}$$

In order to define the mole fraction of water vapor in the air the following equation is used:

$$y_{H_2O} = \frac{ph}{p} = \frac{3.663\ \text{mbar}}{1013.25\ \text{mbar}} = 0.00362 \quad \text{(A4.2)}$$

Finally the relation between the humid air and the dry air can be calculated as follows:

$$\frac{n_{H_2O}}{n_{\text{Dry Air}}} = \frac{y_{H_2O}}{1 - y_{H_2O}} = \frac{0.00362}{1 - 0.00362} = 0.0036282 \ldots \approx 0.36\ \% \quad \text{(A4.3)}$$

The result means that there are only 0.36 % of water vapor and 99.64 % of dry air in the air that is used for combustion in STP-conditions. These calculations are adapted from Raiko et al. (2002) and Cuba (2011).

The composition of the biomass has to be known in order to define the stoichiometric amount of air needed for its combustion. One also needs to be familiar with the reaction equations of carbon (C), hydrogen (H_2) and sulphur (S) to know how much oxygen they consume in combustion and which products they form. The reactions are

$$C + O_2 \rightarrow CO_2, \quad \text{(A4.4)}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad \text{(A4.5)}$$

and

$$S + O_2 \rightarrow SO_2 \quad \text{(A4.6)}$$

The following calculations are for 100 kg of bamboo which moisture content is 15 w-%. The weight percents are the same ones that were used in Thermoflex simulations. The last column tells the consumption of oxygen which is based on the above reactions (A4.4-A4.6). Nitrogen and water are inert and do not react.

Table A4.2 *The stoichiometric combustion of bamboo.*

	Weight-%	m (kg)	M (kg/kmol)	n (kmol/100kg bamboo)	Product	O consump-tion	Stoichiometric O consump-tion
C	0.39039	39.04	12.011	3.2503	CO_2	2	6.5005
H	0.05014	5.01	1.008	4.9750	H_2O	0.5	2.4875
O	0.37101	37.10	15.999	2.3190		-1	-2.3190
N	0.00143	0.14	14.007	0.0102	N_2	0	0
S	0.00018	0.02	32.066	0.0006	SO_2	2	0.0011
H_2O	0.15	15	18.015	0.8326		0	0
Ash	0.03684	3.68	-	-	-	-	-
Σ	1	100.00				**Tot.**	**6.6702**

As seen in table A4.2, 100 kg of bamboo needs 6.67 kmol of oxygen (O) to burn completely. The gasification agent in the gasifier of Huatusco is **air** so the amount of air has to be defined next. It is assumed that air consists only of nitrogen (79 %) and oxygen (21 %).

Table A4.3 *The amount of air needed for complete combustion of bamboo.*

n_{O2} = 6.6708/2 =	3.335	kmol / 100 kg bamboo	
$n_{air} = n_{O2}+(79/21)*n_{O2}$ =	15.908	kmol / 100 kg bamboo	
n_{H2O} in the air = 0.0036 * n_{air} =	0.0577	kmol / 100 kg bamboo	
Humid air needed = $n_{air} + n_{H2O}$ =	**15.966**	kmol / 100 kg bamboo	
$m_{air} = n_{air}*M_{air} + n_{H2O}*M_{H2O}$=	**461.821**	kg /100 kg bamboo	
R	8.314	J/molK	
T_{air}	273.15	K	
p_{air}	101325	Pa	STP
M_{air}	28.9647	kg/kmol	
$\rho_{air} = p_{air}* M_{air}/R* T_{air}$ =	1.292	kg/m^3	
$V_{air} = m_{air} / \rho_{air}$ =	**356.550**	Nm^3 / 100 kg bamboo	

In standard conditions (T=0 °C and p=101325 Pa) 15.97 kmol, 461.82 kg or 356.55 m^3 of air is needed for stoichiometric combustion of 100 kg of bamboo. The humidity of the air does not practically affect the results in STP conditions.

When the mass flow of bamboo and the equivalence ratio are known, the mass flow of air (=A) needed for gasification of 62.9 kg/h of bamboo, can be defined. The calculations are shown in table A4.4.

Table A4.4 *The mass flow of the actual air used for gasification.*

F (initial value)	62.9	kg bamboo/h
ER (initial value)	0.374	-
$(A/F)_{stoic} = m_{air}/100 =$	4.618	kg air/kg bamboo
$(A/F)_{real} = ER*(A/F)_{stoic} =$	1.727	kg air/kg bamboo
$A_{stoic} = F*(A/F)_{stoic} =$	290.485	kg air/h
$A_{real} = F*(A/F)_{real} =$	**108.642**	**kg air/h**

It can be seen that the mass flow of air needed for gasification is 108.64 kg/h. All these calculations were adapted from Raiko et al. (2002) and Cuba (2011).

Composition and Heating Value of the Synthesis gas

At first the total moles of all the different components present in the process are calculated. The column "n" is copied from table A4.2. In order to know the amount of oxygen and nitrogen in the air used in gasification, the stoichiometric moles (6.67 kmol of table A4.2) are multiplied by the equivalence ratio. In the last column the total amount of each component is summed.

Table A4.5 *The total moles of substances entering the gasifier.*

	Component	n (kmol)		n_{tot} (kmol)
Bamboo	C	3.2503	$= n_C =$	**3.2503**
	H	4.9750	$= n_H+2*n_{H2Otot} =$	**6.7264**
	O	2.3190	$= n_O+n_{H2Otot}+n_{Oair} =$	**5.6894**
	N	0.0102	$= n_N+n_{Nair} =$	**9.3948**
	S	0.0006	$= n_S =$	**0.0006**
	H_2O	0.8326	$= n_{H2O} + n_{H2Oair}$	**0.8757**
Air	O_{air}	$= 6.81*ER =$	2.4946	
	N_{air}	$= 6.81*ER*(79/21) =$	9.3846	
	H_2O_{air}	$= (O_{air}+N_{air})*0.0036 =$	0.0431	

To find out the composition of the gas, the mass balances are used. In table A4.6 below, it can be seen that the components that contain carbon in the synthesis gas are CO, CO_2 and CH_4. The mole percentages are obtained from the simulation of Thermoflex and they are used as a reference in order to define the gas composition. The next column shows the molecular weight of the components. "C weight per mole" in the next column means the weight of carbon in each component. The last column shows the densities defined in the STP conditions.

Table A4.6 *The carbon including components of the synthesis gas.*

Component	mole-%=V-%	M (g/mol)	C weight per mole (g/mol)	Density, STP (kg/m^3)[1]
H_2				
H_2O				
N_2				
CO	**16.81**	28.01	12.011	1.251
CO_2	**12.40**	44.01	12.011	1.977
CH_4	**0.0015**	16.04	12.011	0.718
H_2S				
Ar				

[1] Source: http://www.wolframalpha.com/, (inputs: "gas name" density 0 °C), accessed on 18.8.14.

Now the volumetric fraction of carbon in the synthesis gas (v_C) can be calculated as follows. The method has been adapted from the thesis of Gunarathne (2012) and it is originally part of Modified Loss Method A4 (Huisman 2000).

$$v_C = \sum \frac{v_C \text{ of components that contain C} * \text{Density} * \text{C weight per mole}}{\text{Molecular weight of the component}}$$

$$= \left(\frac{0.1681 * 1.251 \frac{kg}{m^3} * 12.011 \frac{g}{mol}}{28.01 \frac{g}{mol}} \right) + \left(\frac{0.1240 * 1.977 \frac{kg}{m^3} * 12.011 \frac{g}{mol}}{44.01 \frac{g}{mol}} \right) + \left(\frac{1.5e^{-5} * 0.718 \frac{kg}{m^3} * 12.011 \frac{g}{mol}}{16.04 \frac{g}{mol}} \right) = 0.157 \frac{kg}{m^3} \quad \text{(A4.7)}$$

By dividing each of the fractions by the V_C, the following results are obtained:

Table A4.7 *The carbon balance of the synthesis gas.*

Fraction	%
v_{CO}	57.40
v_{CO2}	42.59
v_{CH4}	0.0051
Σ	100.00

These percentages of carbon compounds are used as a base for the following mass balance calculations. The composition of the synthesis gas is obtained through the balance. The lowest row shows the same amounts of kilo moles than in table A4.5.

Table A4.8 *The syngas composition obtained by mass balance of the components.*

Compound	%	C	N	O	H	S	n_i (kmol)	Y_i (vol-%)
CO	57.40	1.866		1.866			1.8657	16.49
CO_2	42.59	1.384		2.769			1.3843	12.24
CH_4	0.0051	0.000			0.001		0.0002	0.00
N_2			9.395				4.6974	41.53
H_2O				1.055	2.110		1.0551	9.33
H_2					4.615		2.3076	20.40
H_2S					0.0003	0.0006	0.0006	0.00
Σ	100.00	3.250	9.395	5.689	6.726	0.0006	**11.3108**	**100.00**

By knowing the total moles (11.31 kmol) of the produced gas, the volumetric flow of the syngas can be defined utilizing the molar volume of gas, V_m. The volumetric flow of the gas (=G) in standard conditions can be seen in table A4.9 below.

Table A4.9 *The G/F-ratio and the volumetric gas flow.*

V_m	22.41	Nm^3/kmol
n_{gas}	11.3108	kmol/100 kg bamboo
$V_{gas} = V_m * n_{gas}$ = G/F-ratio	**2.53**	Nm^3/1 kg bamboo
$G = V_{gas} * F$ =	**159.44**	Nm^3/h

The gas composition is needed for calculating the heating value of the gas. Only the carbon monoxide, methane and hydrogen have heating values as seen in table A4.10. The last columns of the table shows the molar mass of the synthesis gas.

Table A4.10 *Calculations of the lower heating value of the synthesis gas.*

Product	M (g/mol)	Y_i (vol-%)		LHV (kJ/Nm^3) [1]	LHV*Y_i (kJ/Nm^3)		M_i*Y_i (g/mol)	
		Humid	Dry		Humid	Dry	Humid	Dry
CO	28.01	16.49	18.19	12625	2082.42	2296.66	4.62	5.10
CO2	44.009	12.24	13.50	0	0	0	5.39	5.94
CH4	16.043	0.0015	0.0016	35796	0.53	0.58	0.00	0.00
N2	28.014	41.53	45.80	0	0	0	11.63	12.83
H2O	18.015	9.33	0.00	0	0	0	1.68	0
H2	2.016	20.40	22.50	10789	2201.16	2427.62	0.41	0.45
H2S	34.082	0.005	0.01	0	0	0	0.00	0.00
Σ		100.00	100.00		**4284.11**	4724.86	**23.73**	24.32

[1]Waldheim 2001, p. 24 & p.42

The lower heating value in the normal conditions with the given initial values is found out to be 4284.11 kJ/Nm^3. The calculations of the gas composition and the heating value were adapted from Cuba (2011).

Engine-Generator

When the syngas flow and the heating value of the gas are known, the maximum outputs of a genset can be calculated.

Table A4.11 *The maximum outputs of an internal combustion engine (ICE)*

G =the real intake of the ICE	= 159.44*3600s =	159.44 0.044	Nm^3/h Nm^3/s
LHV		4284.11	kJ/Nm^3
Thermal power of the gas	= 0.044*4284.11 =	189.73	kW
Compression ratio		10.5:1	-
Efficiency (see section 5.6)		0.28	-
Maximum mechanical output of the ICE	= 0.28*189.73 =	53.13	kW
Generator Efficiency (see section 5.6)		0.86	-
Maximum electrical output of the ICE	=0.86*53.13 =	45.69	kW